PULSAR WIND NEBULAE

AND THEIR IMPORTANCE FOR GAMMA-RAY PHYSICS

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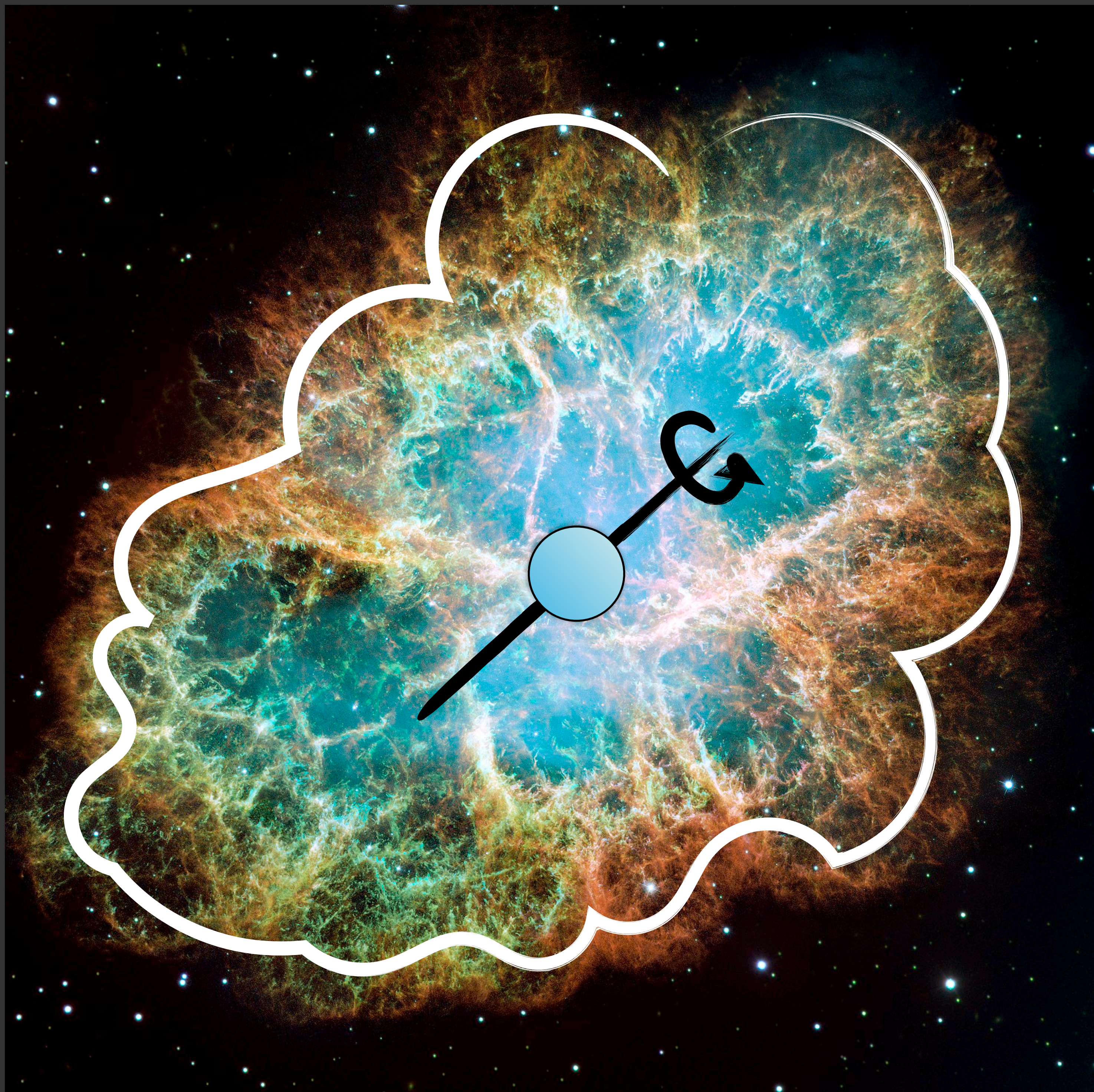
INAF

7th Heidelberg International Symposium on High Energy Gamma-Ray Astronomy

γ 2022 BARCELONA

WHAT IS A PWN?

THE DEBRIS OF THE SUPERNOVA EXPLOSION OF A MASSIVE STAR ($M \gtrsim 8\ M_{\odot}$)



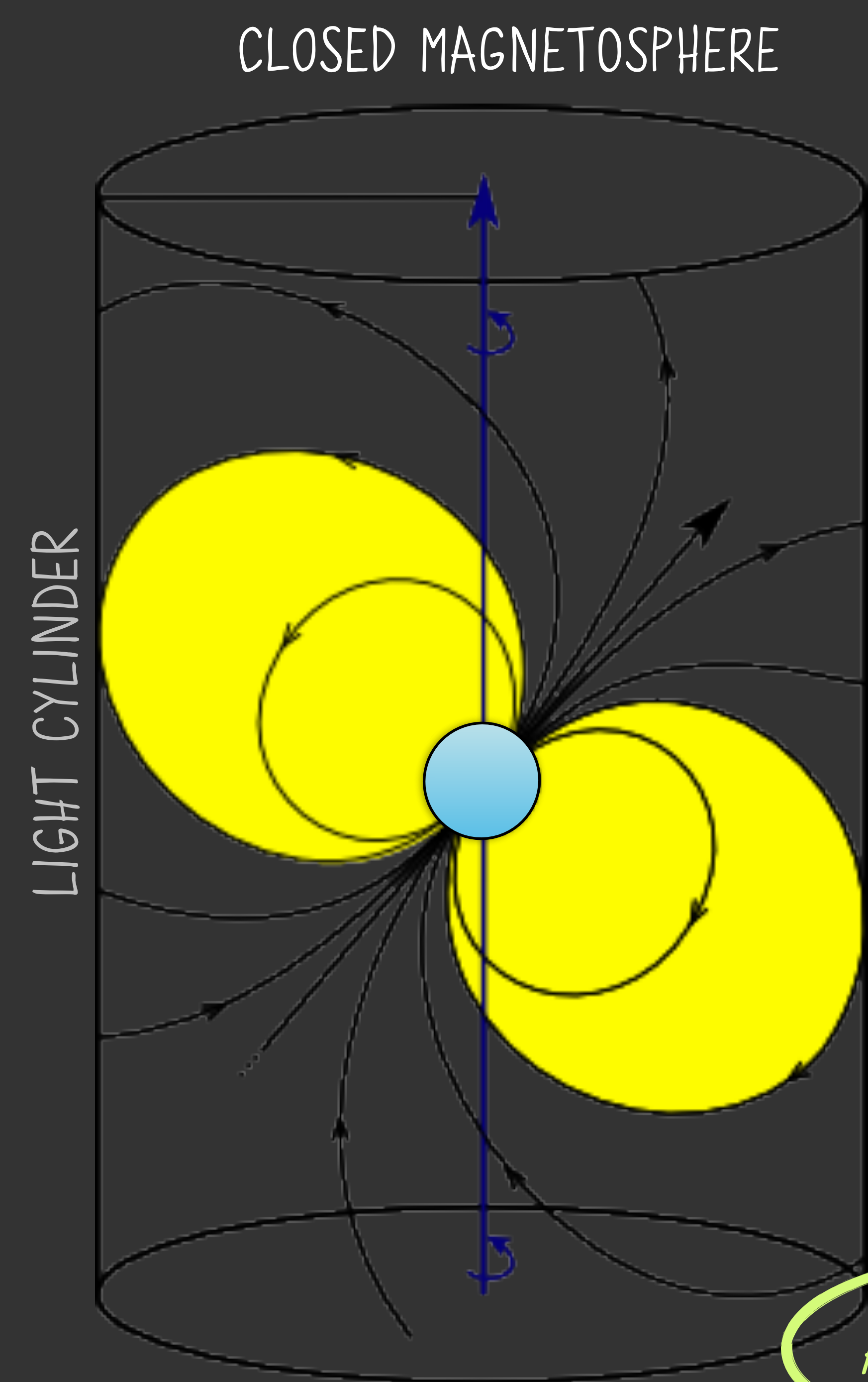
[NOT IN SCALE!!]

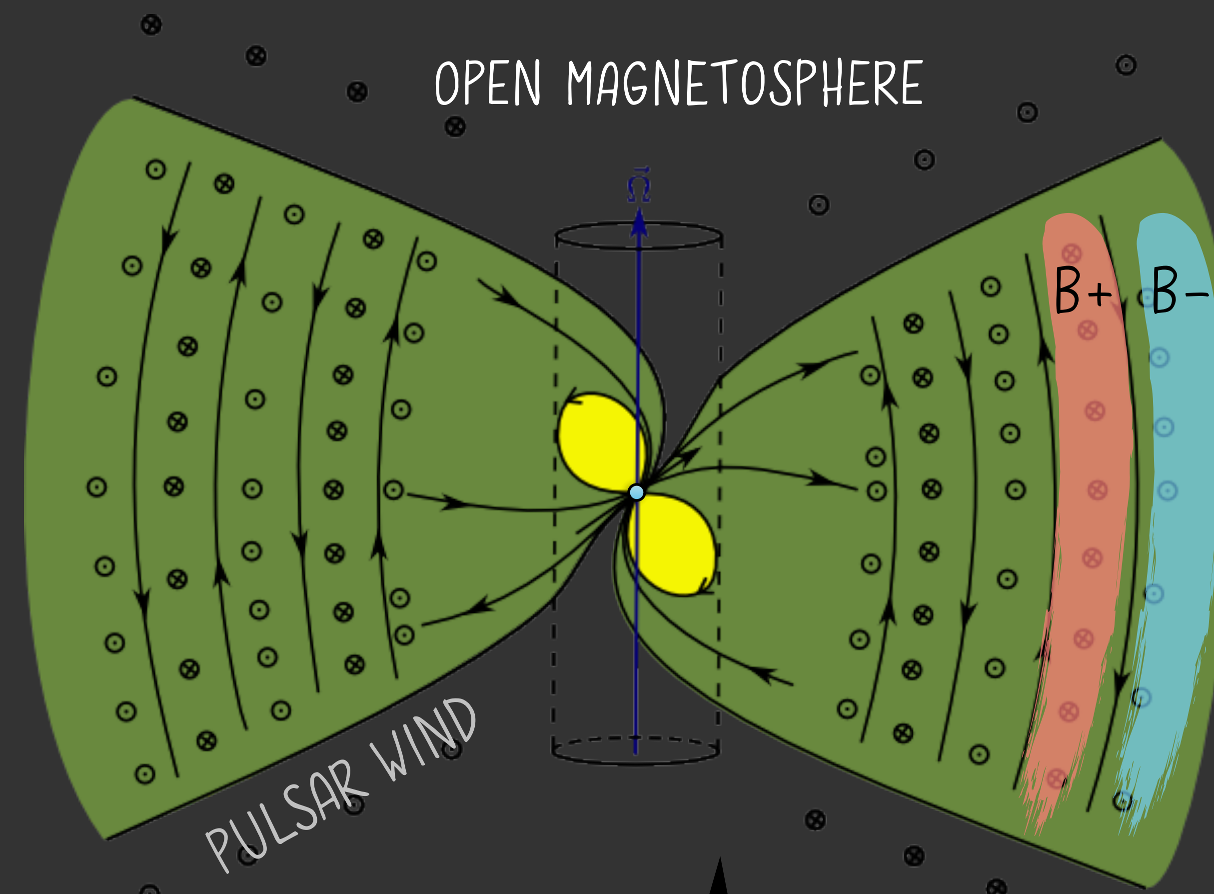
MAIN INGREDIENTS

- THE RAPIDLY ROTATING NEUTRON STAR (PULSAR)
- EJECTA OF THE STELLAR EXPLOSION

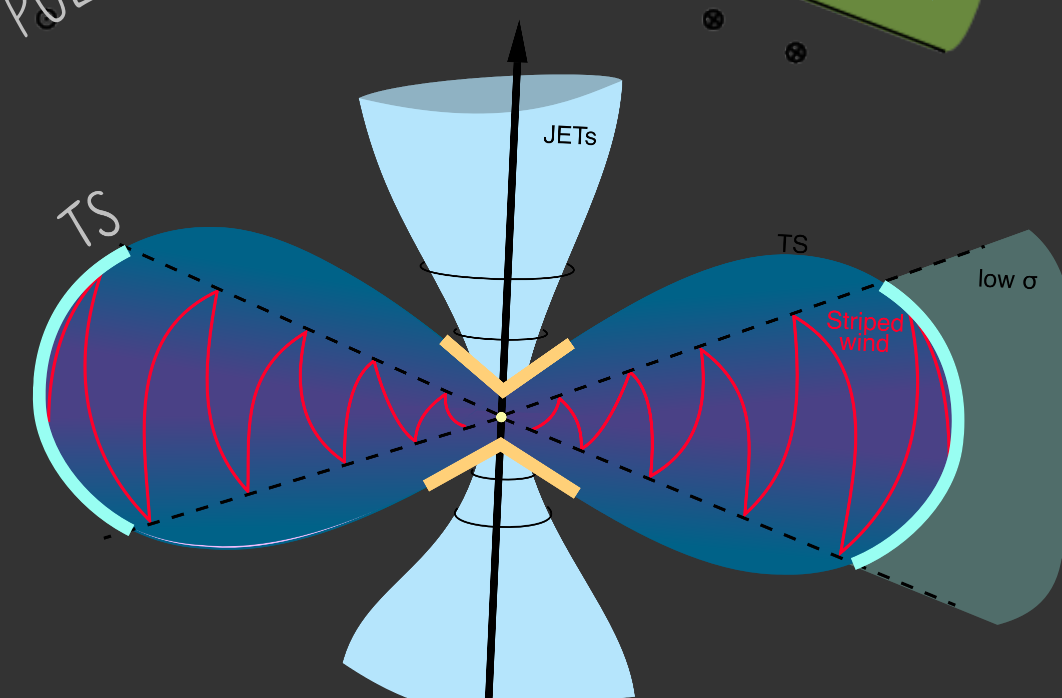
THE PULSAR IS THE ENGINE

PULSAR = ROTATING MAGNET THAT SLOWS DOWN DUE TO ELECTROMAGNETIC TORQUE [PACINI 1969]
PRODUCING AN OUTFLOW IN THE FORM OF RELATIVISTIC PARTICLES AND MAGNETIC FIELD: THE PULSAR WIND



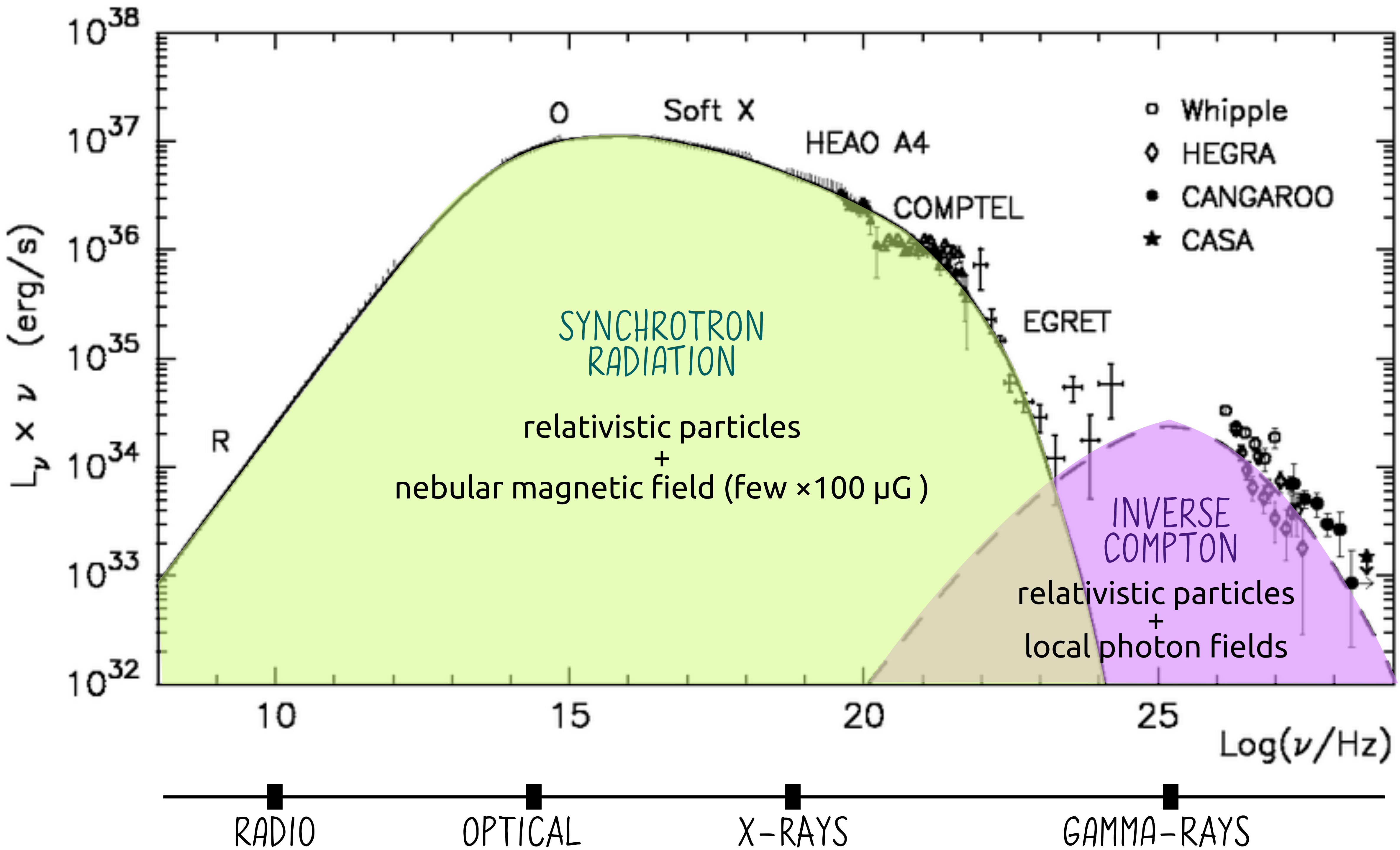


ANDREY'S TALK



[Fig. from Amato & Olmi 2022]

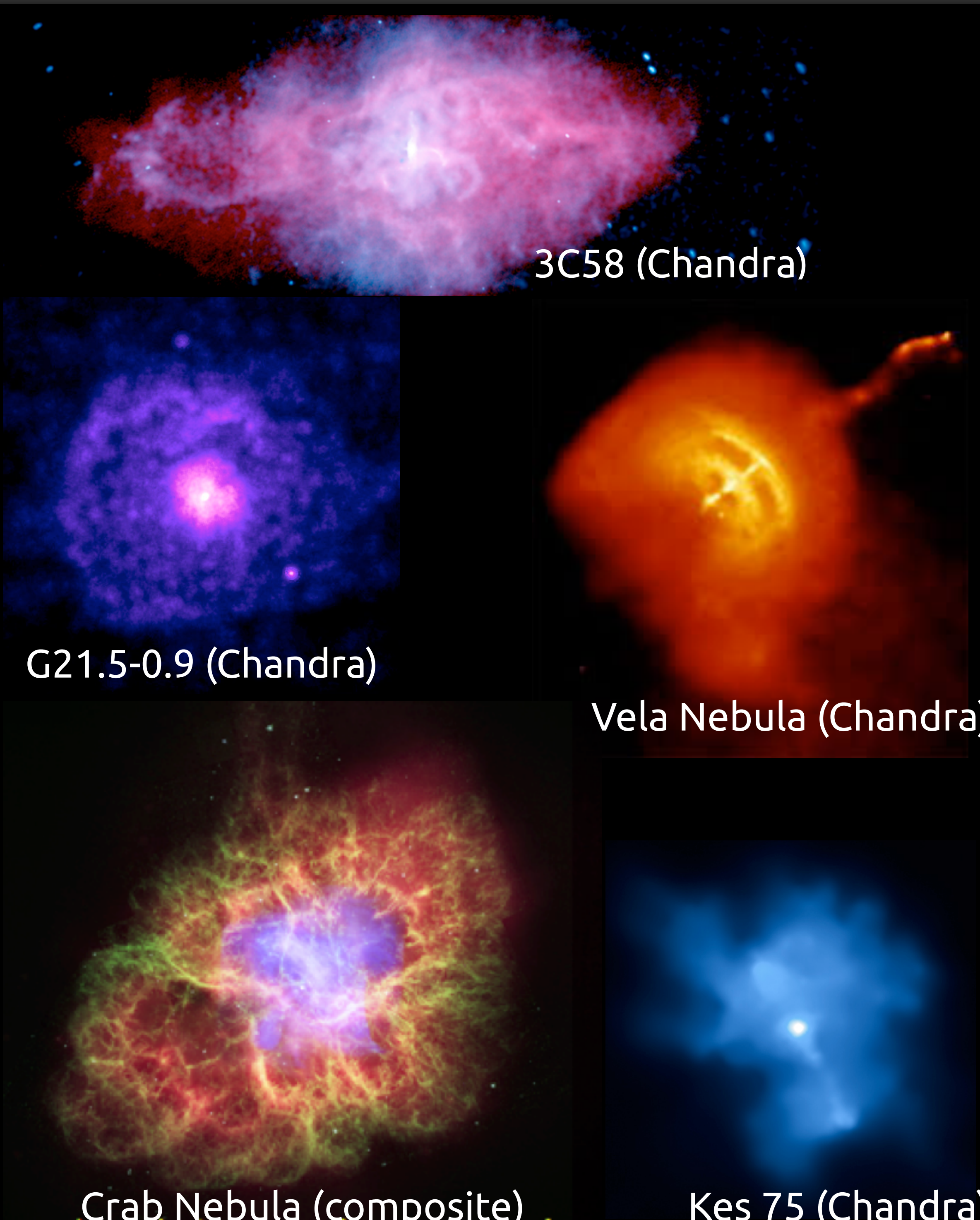
HOW DO THEY LOOK? BROAD BAND NON-THERMAL SPECTRUM



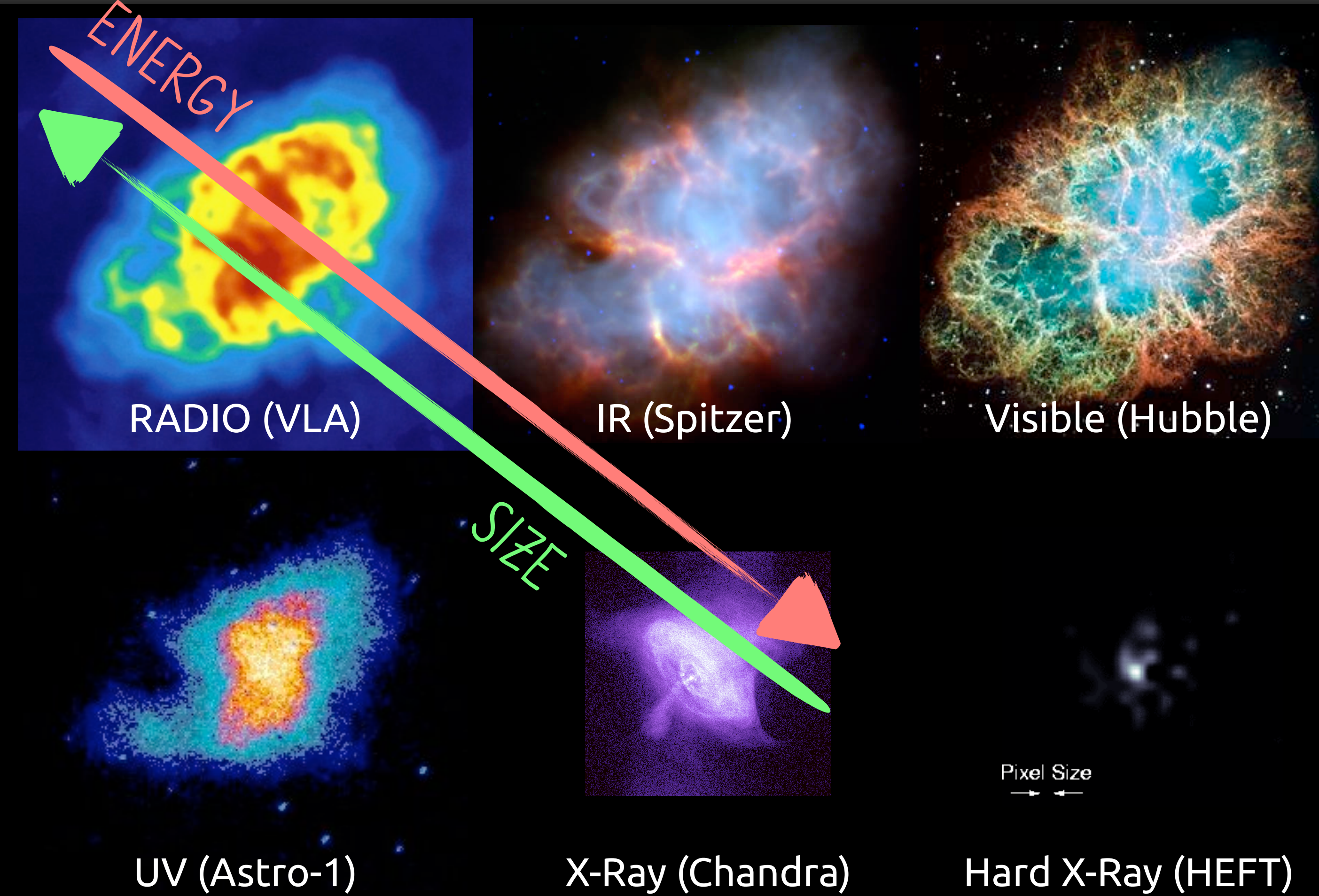
The CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]

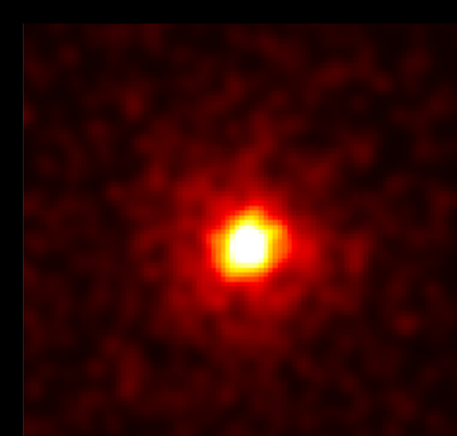
HOW DO THEY LOOK?
YOUNG SYSTEMS @ MULTI-FREQUENCY

Fill-centered morphology



Decreasing size with energy



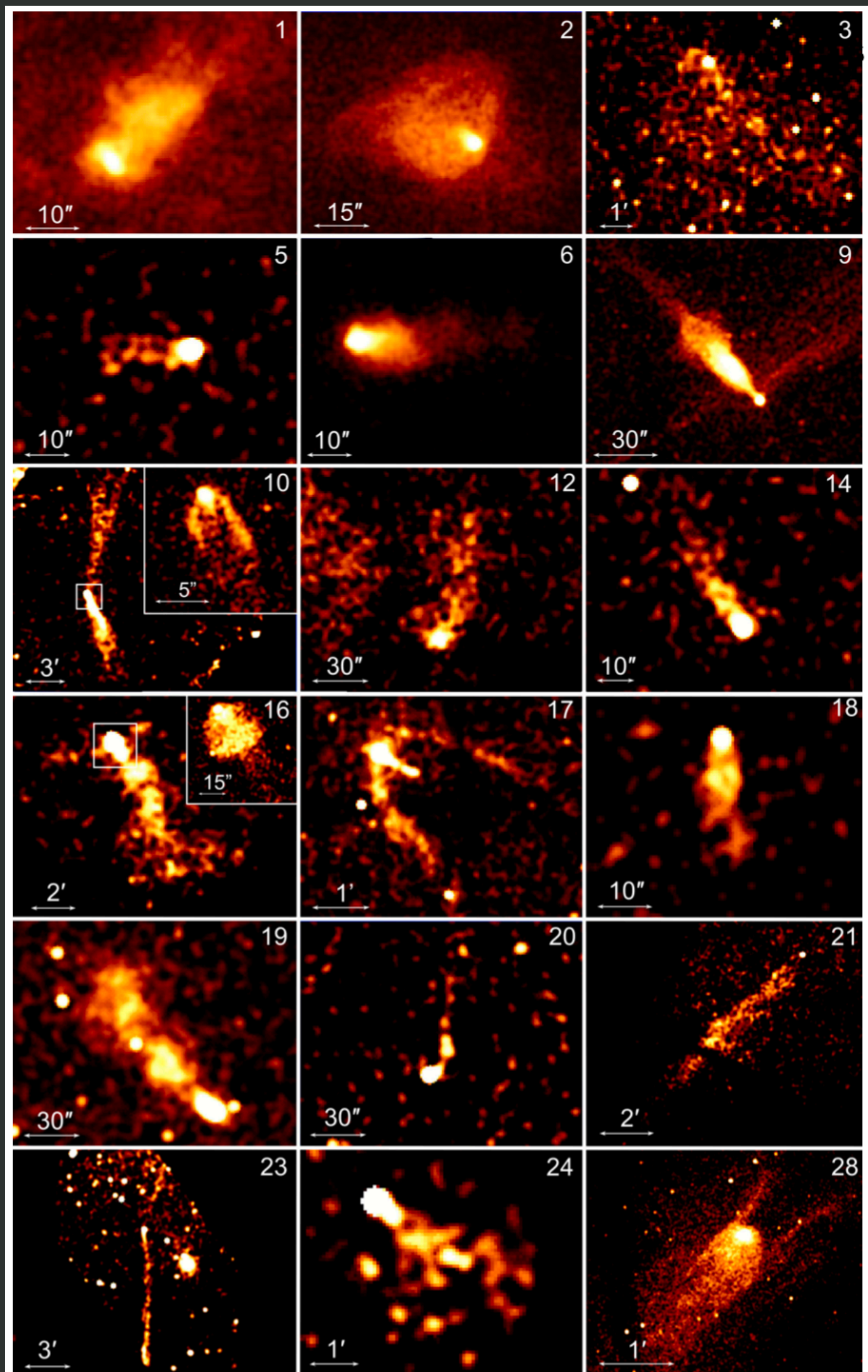


Gamma-rays

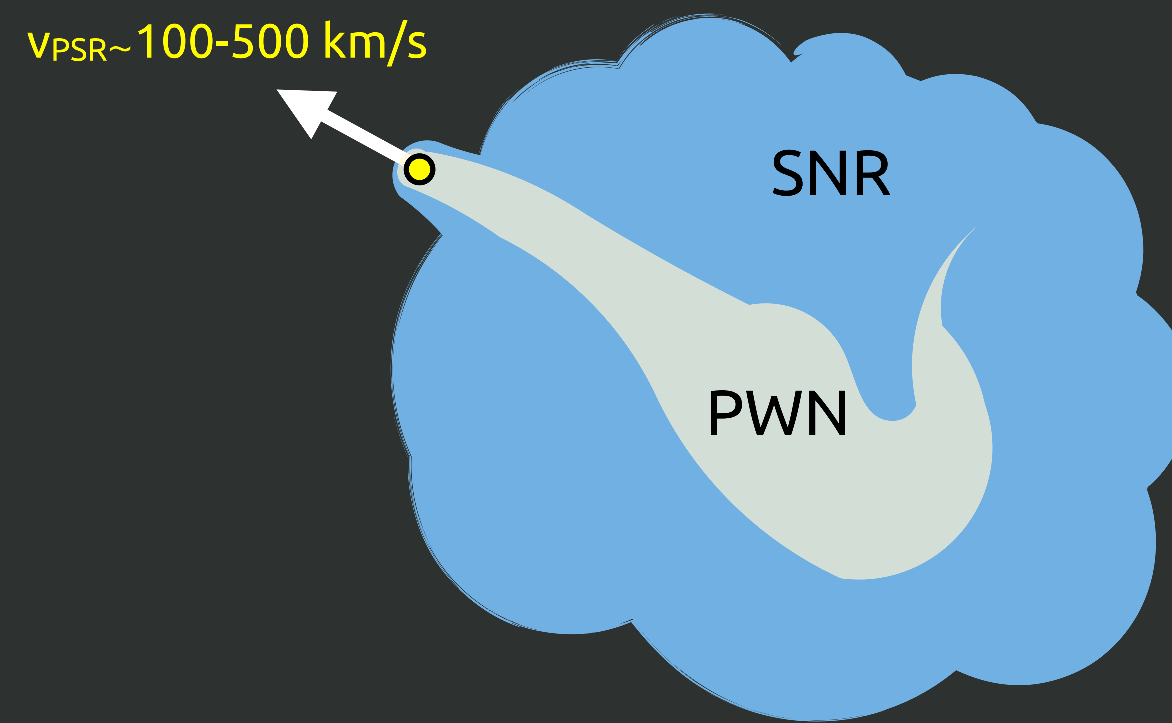
Morphology poorly resolved @ gamma-rays

HOW DO THEY LOOK?
OLD SYSTEMS

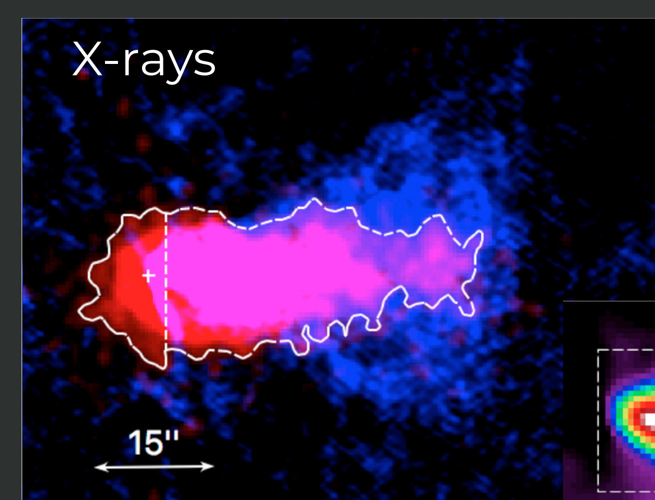
X-ray (Chandra)



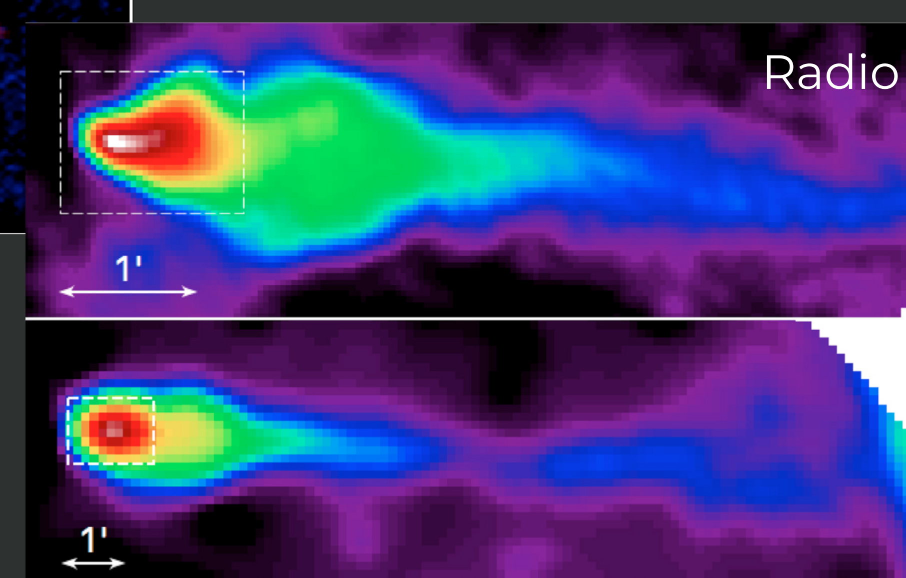
Kargaltsev et al. 2017



Typical ISM sound speed:
c_s~10-100 km/s ~ 1/10 v_{PRS}

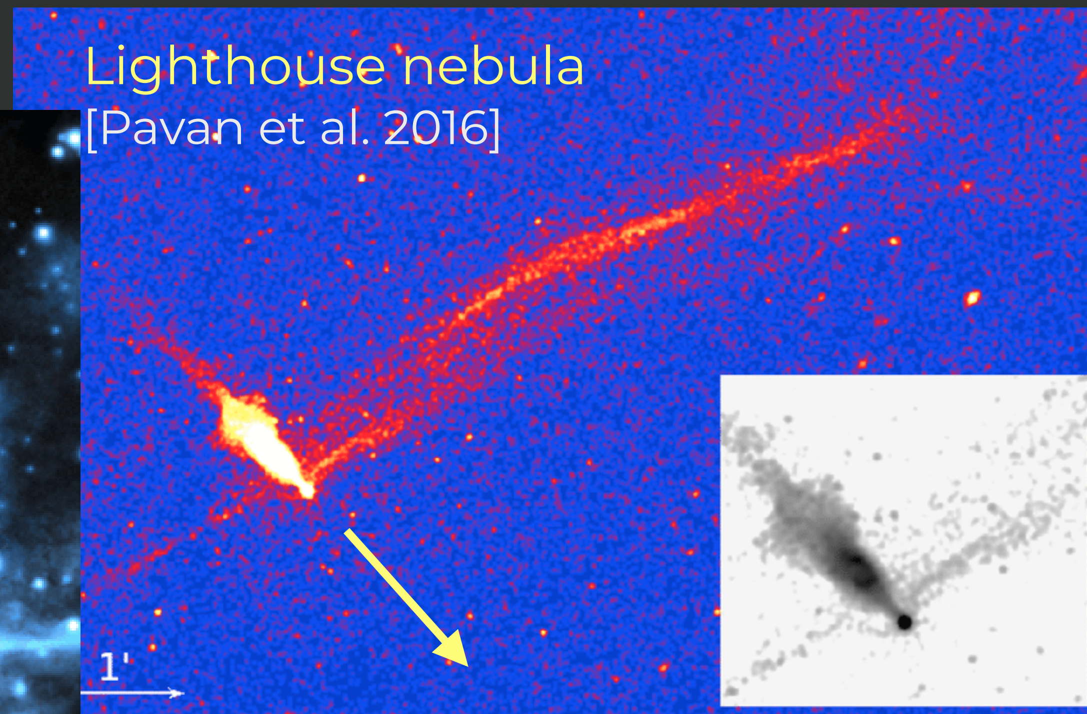


Mouse PWN
[Yusef-Zadeh & Bally 1987,
Yusef-Zadeh & Gaensler 2005,
Klinger et al. 2018]



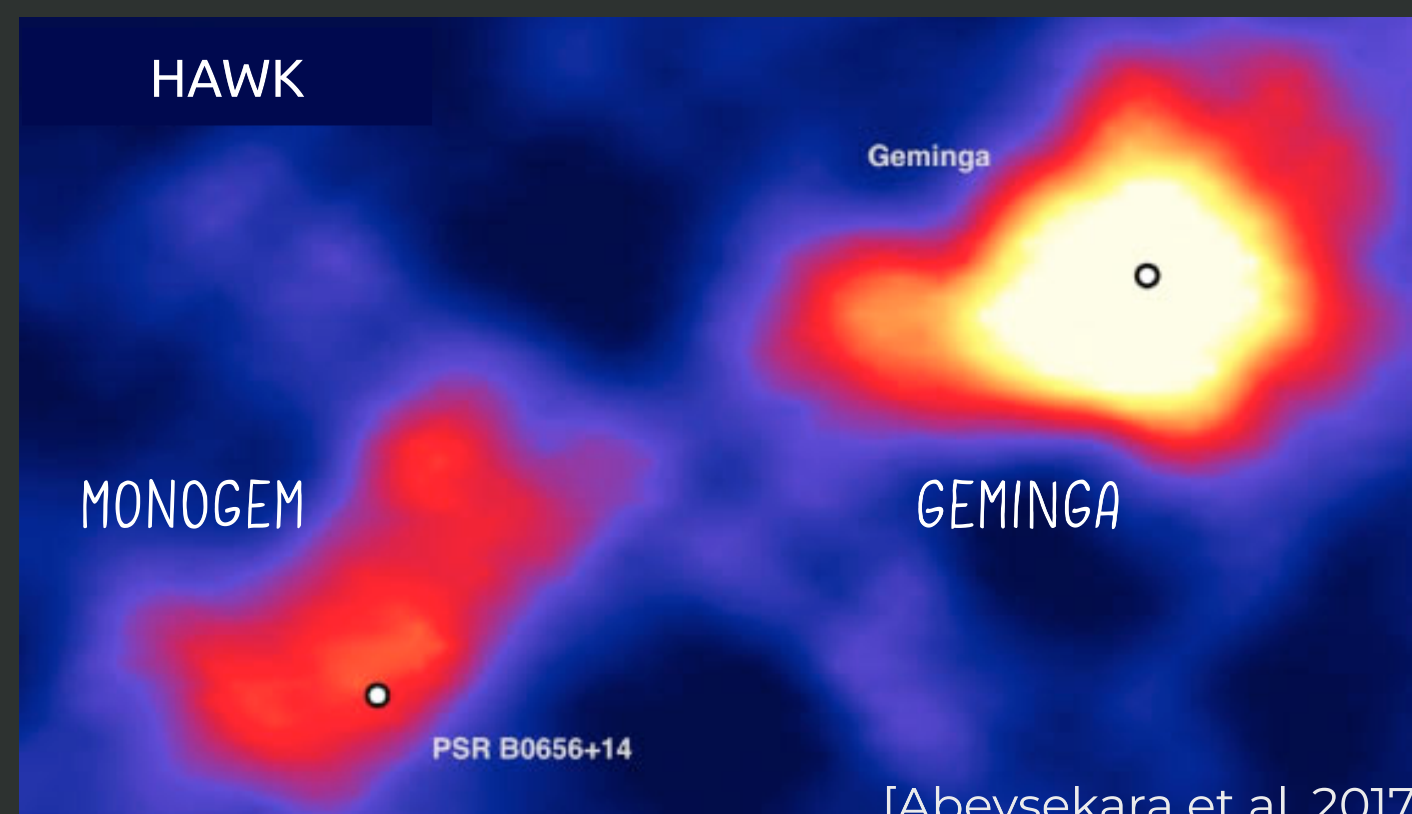
PARTICLE LEAKAGE FROM OLD SYSTEMS

MISALIGNED X-RAY TAILS



Other cases:
G327 [Temim et al. 2009]
J1509-5850 [Klingler et al. 2016]
J1809-1917 [Klinger et al. 2020]
B1929+10 [Kim et al. 2020]

TEV HALOS



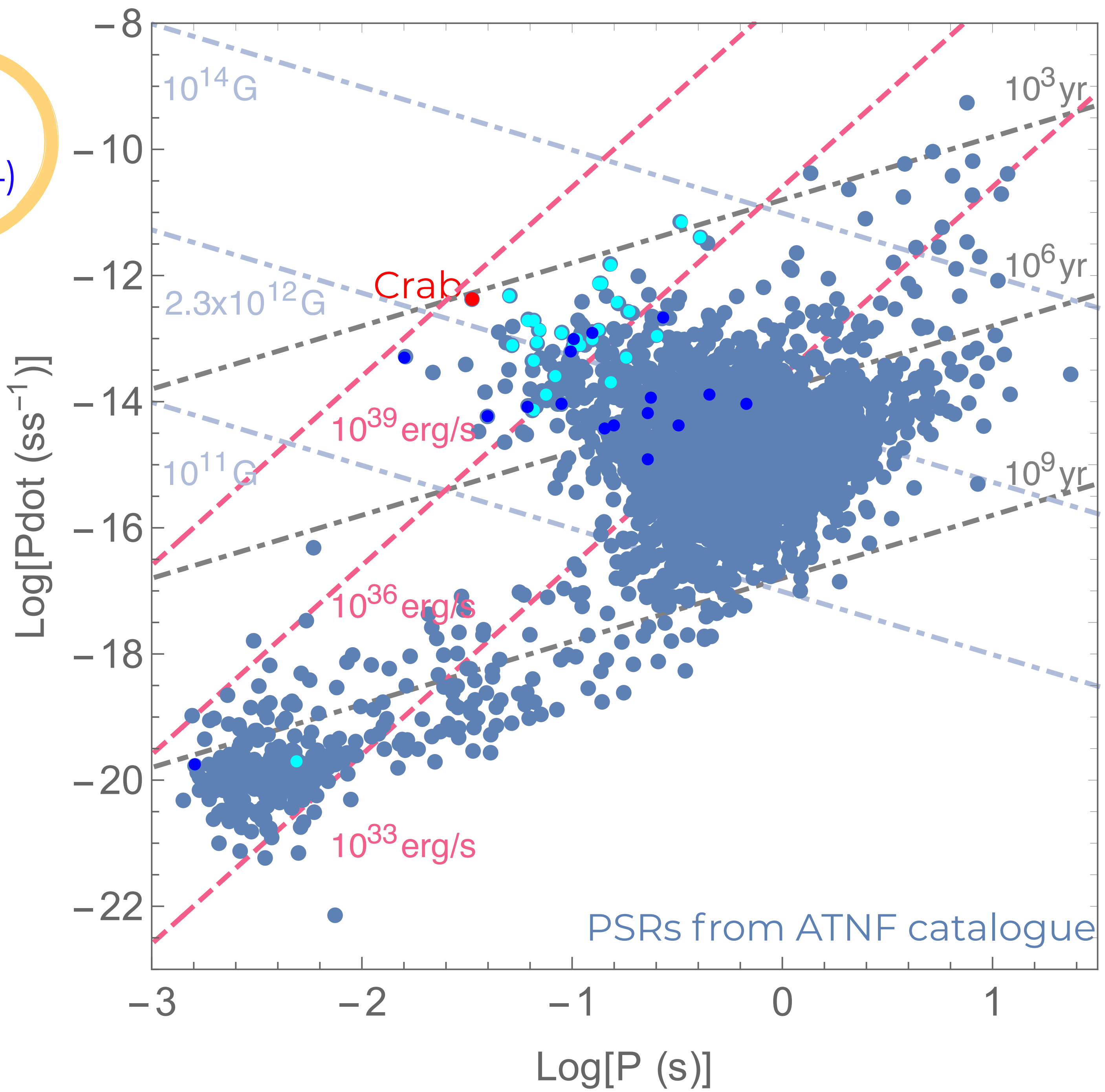
KNOWN PWNE

KNOWN SYSTEMS (FIRMLY IDENTIFIED - MAINLY AT X-RAYS)

Young PWNe (32?)

Bow shock PWNe (24)

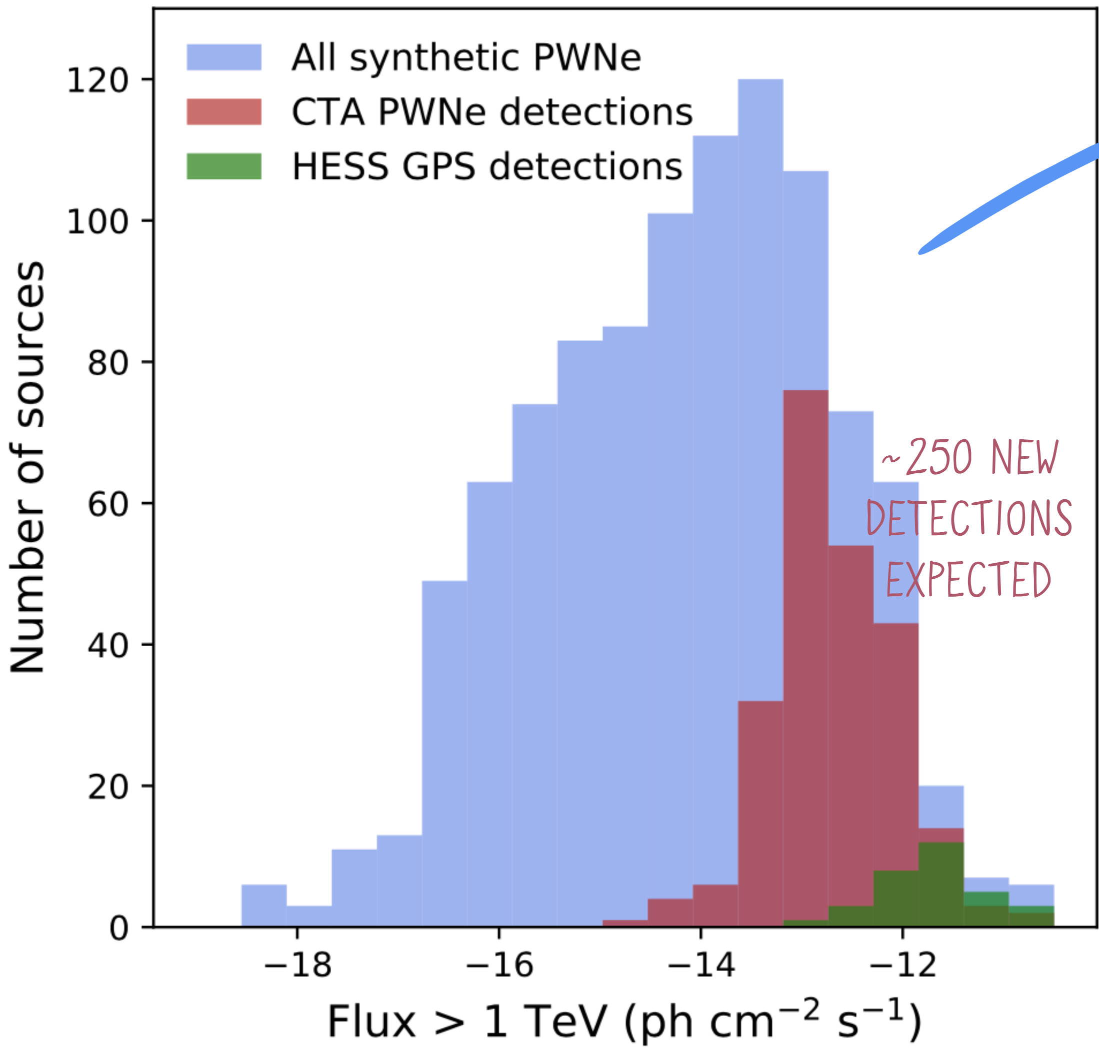
~50 PWNE



[Olmi & Bucciantini, Dawes Review in prep.]

THE FUTURE POPULATION

EXPECTED DETECTIONS AT GAMMA-RAYS WITH CTA

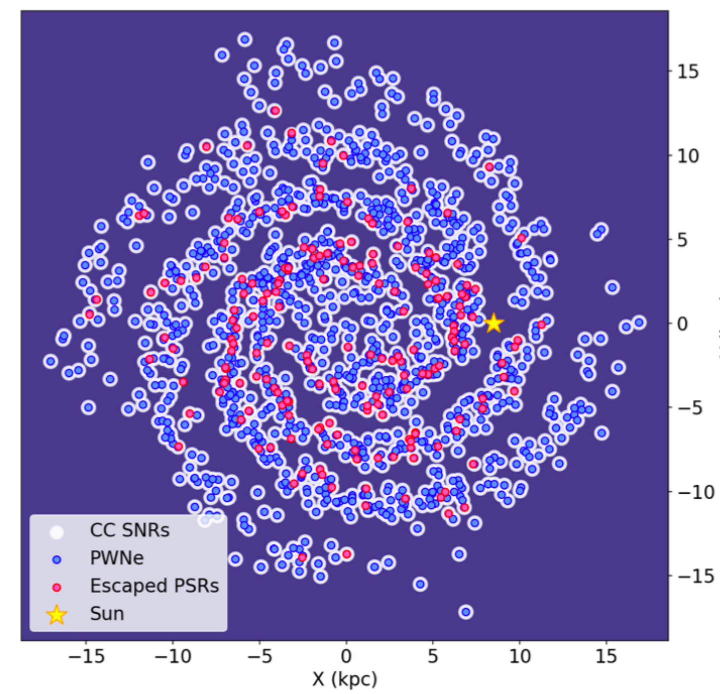


~250 NEW DETECTIONS EXPECTED

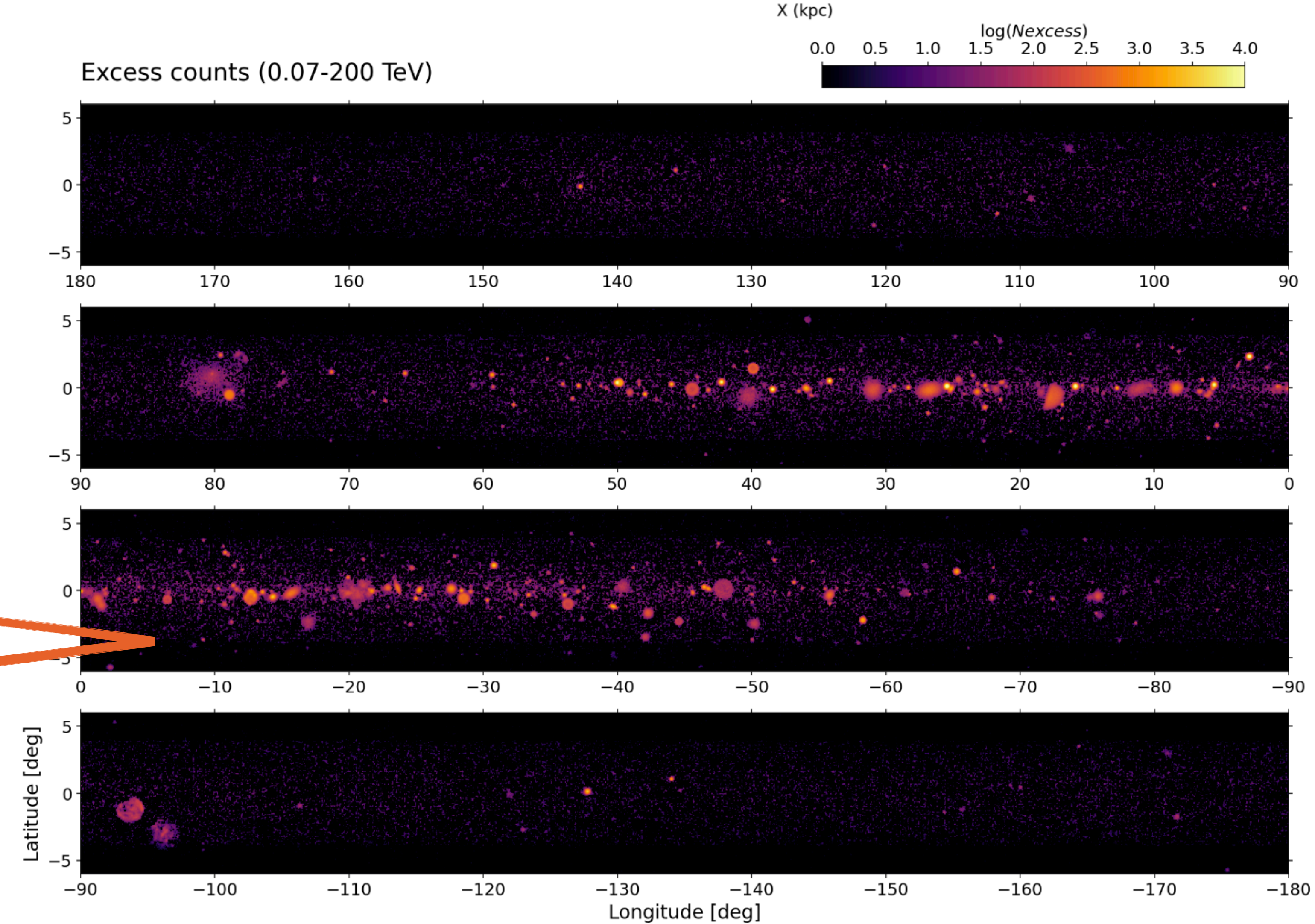
PWNE= 60%
SNRS= 10%

[CTA GPS consortium paper, in prep.]

DISTRIBUTION OF SYNTHETIC SOURCES IN THE GALAXY



[Fiori et al 2022]



[Q. Remy et al. 2021]

WHY ARE PWNE INTERESTING?

- GAMMA-RAY PHYSICS –> MOST NUMEROUS EXPECTED POPULATION IN THE GALAXY!
- PULSAR PHYSICS –> ENCLOSE MOST OF THE ENERGY LOST BY THE PULSAR

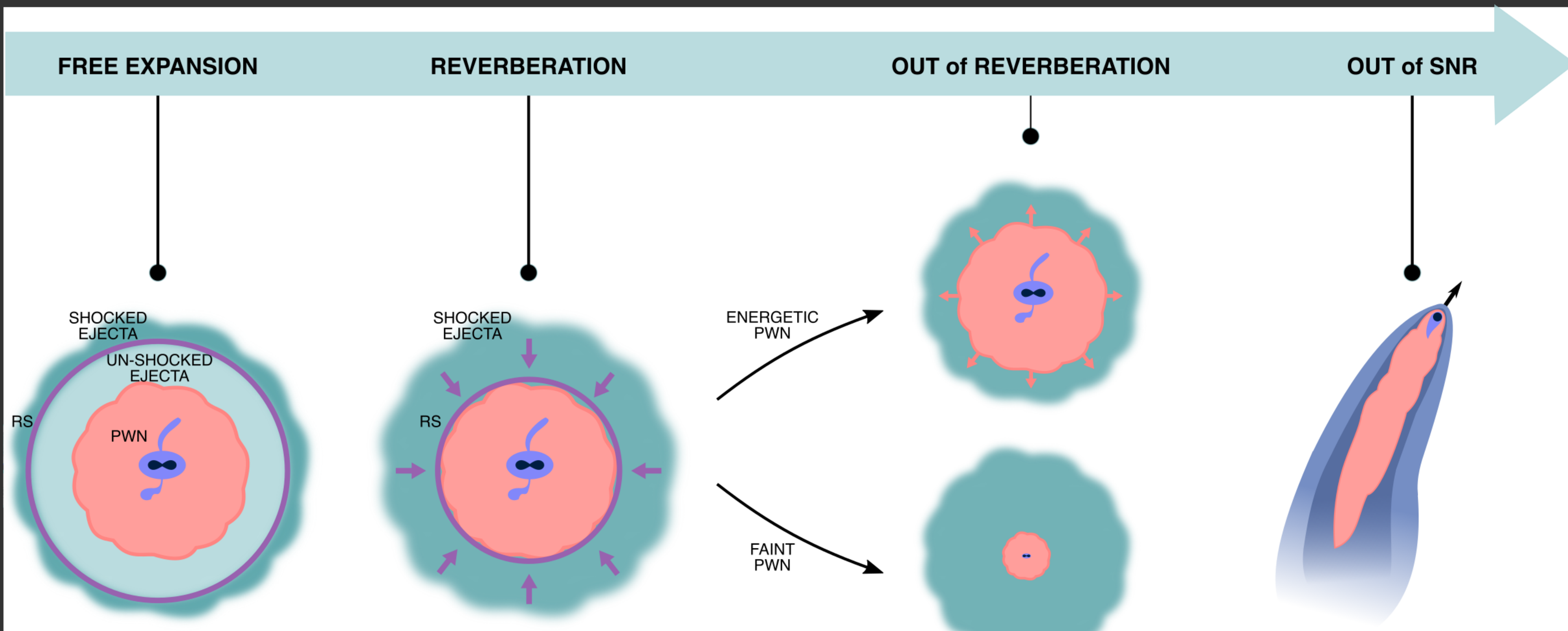
  $L_{radio} \lesssim 10^{-10}\dot{E}_{psr}$ $L_{\gamma} \lesssim 0.01\dot{E}_{psr}$ $L_{PWN} > 0.1\dot{E}_{psr}$

- PLASMA PHYSICS –> EXTREME CONDITIONS IN CLOSE AND BRIGHT SOURCES AND ACCELERATION IN HOSTILE ENVIRONMENT
- CR PHYSICS –> (CRAB) UNIQUE IDENTIFIED LEPTONIC PEVATRONS IN THE GALAXY + ANTIMATTER FACTORIES + PARTICLE LEAKAGE + ALSO HADRONIC PEVATRONS ?

MODELING PWNE

THE DIFFERENT PHASES OF PWN EVOLUTION

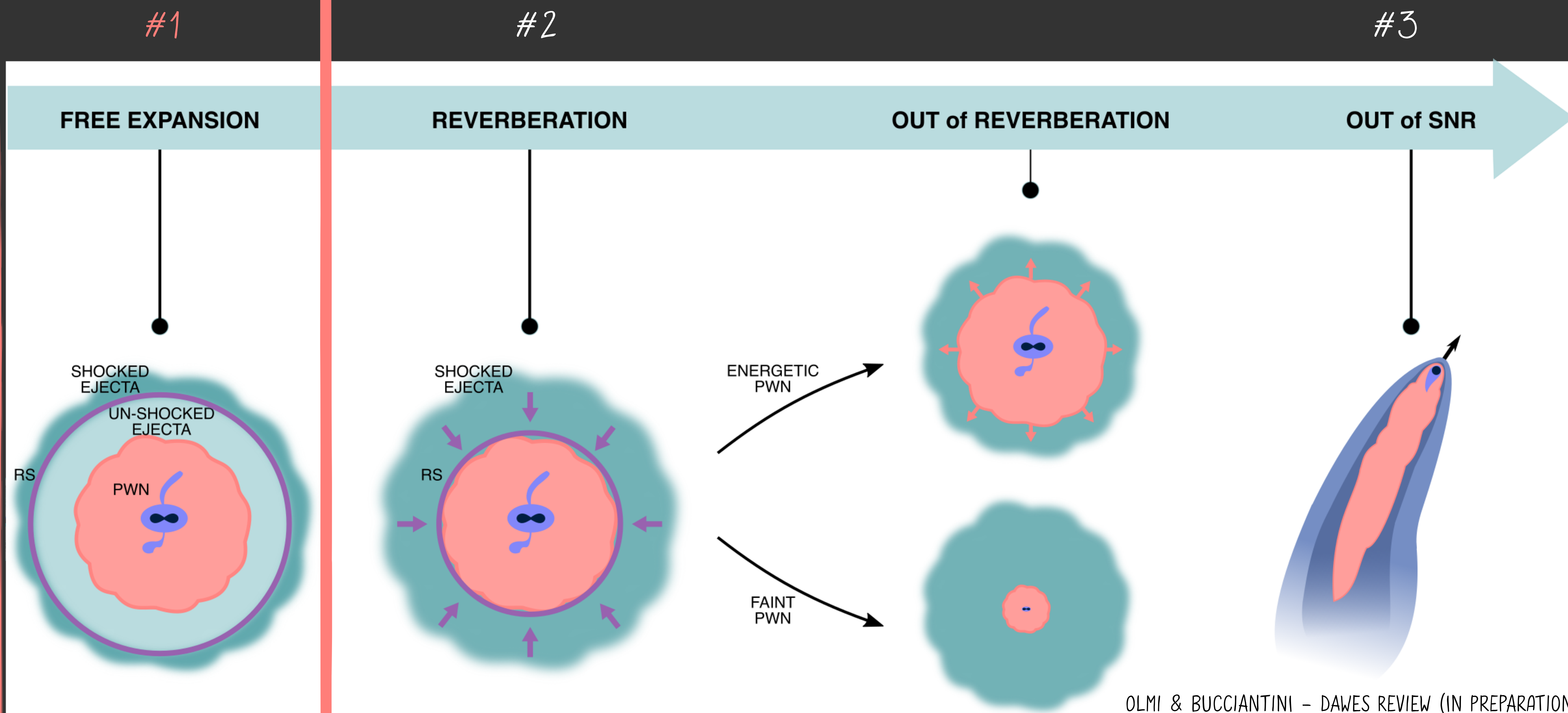
#1 #2 #3



OLMI & BUCCIANTINI – DAWES REVIEW (IN PREPARATION)

MODELING PWNE

THE DIFFERENT PHASES OF PWN EVOLUTION

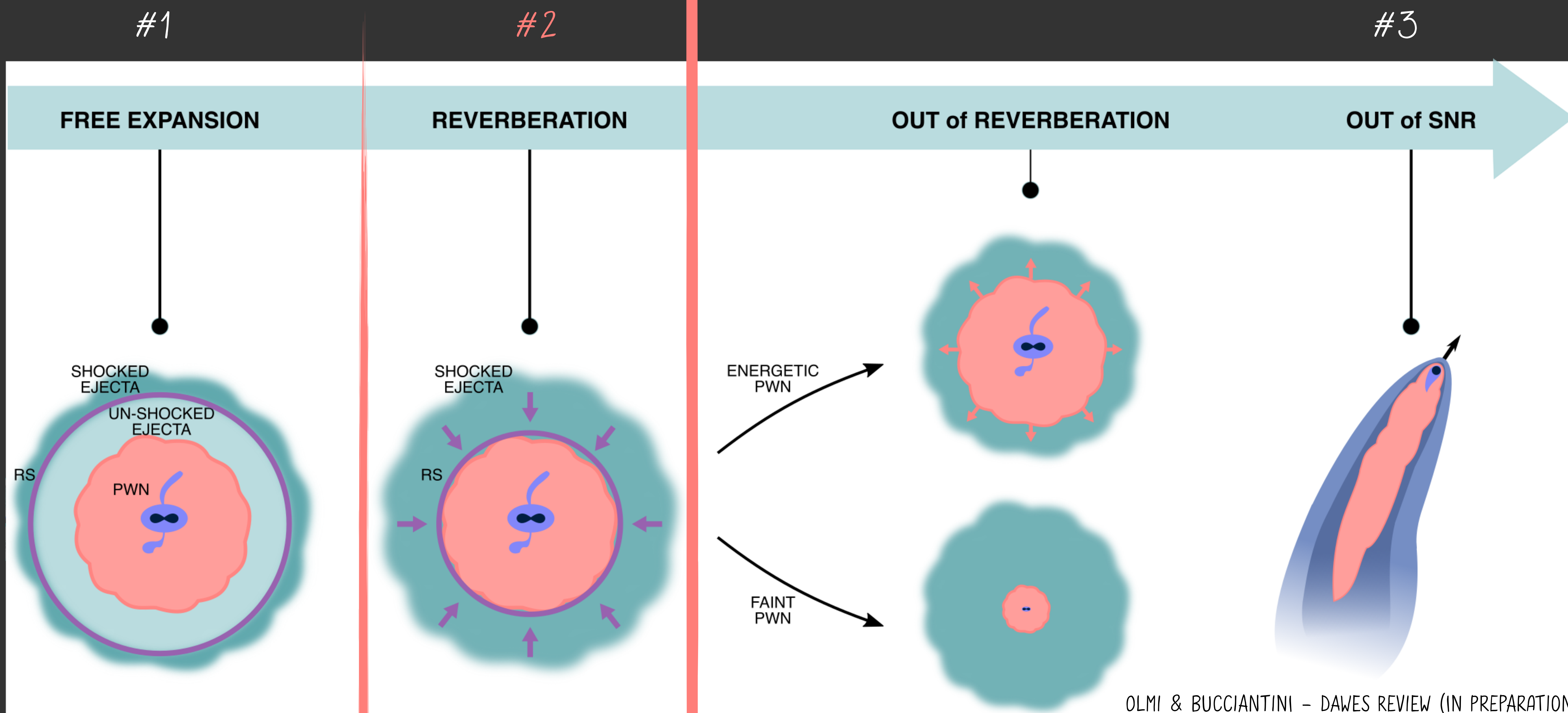


OLMI & BUCCIANTINI – DAWES REVIEW (IN PREPARATION)

WIDELY STUDIED WITH DIFFERENT MODELS (ONE-ZONE –> MULTI-D HD, MHD SIMS)

MODELING PWNE

THE DIFFERENT PHASES OF PWN EVOLUTION



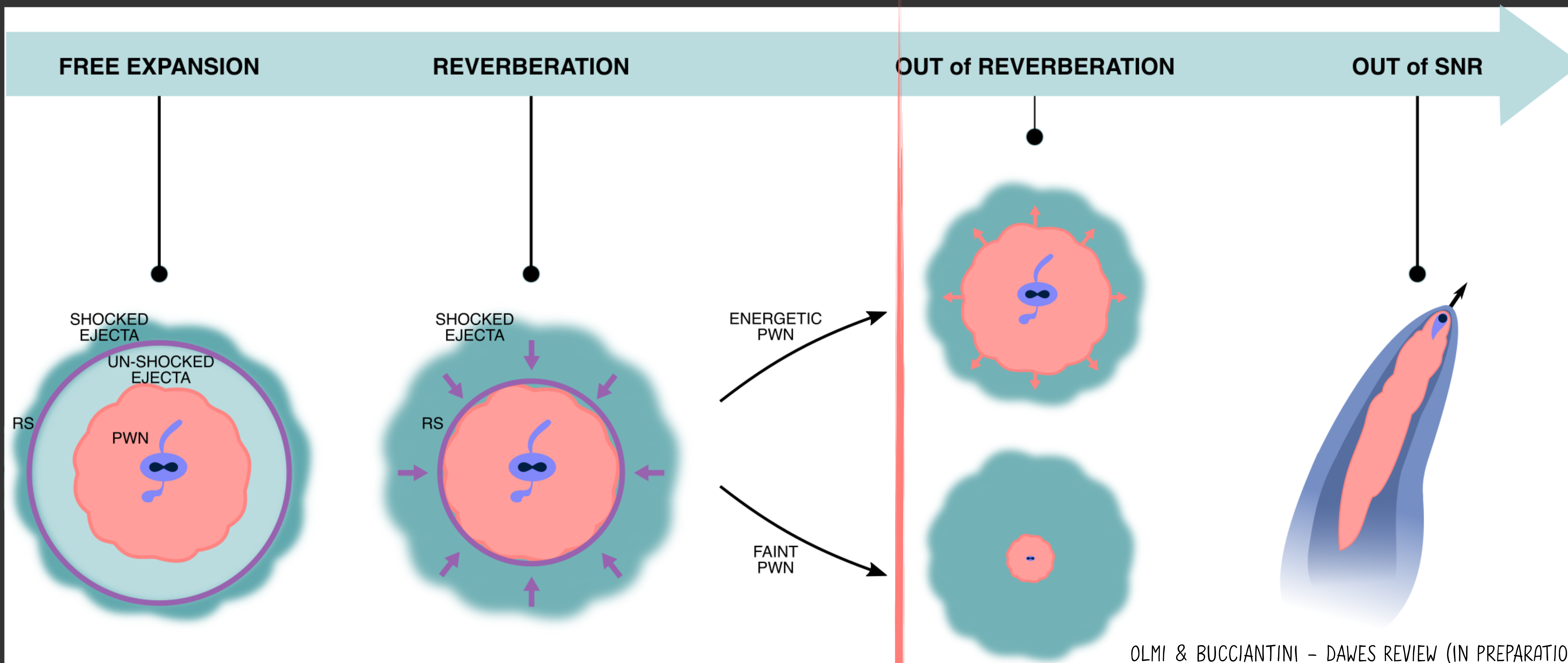
CRITICAL

NOT PROPERLY ACCOUNTED FOR IN THE PAST

MODELING PWNE

THE DIFFERENT PHASES OF PWN EVOLUTION

#1 #2 #3



TRANSITION (COMPLEX PHASE)
+ OLD SYSTEMS (BOW SHOCKS)

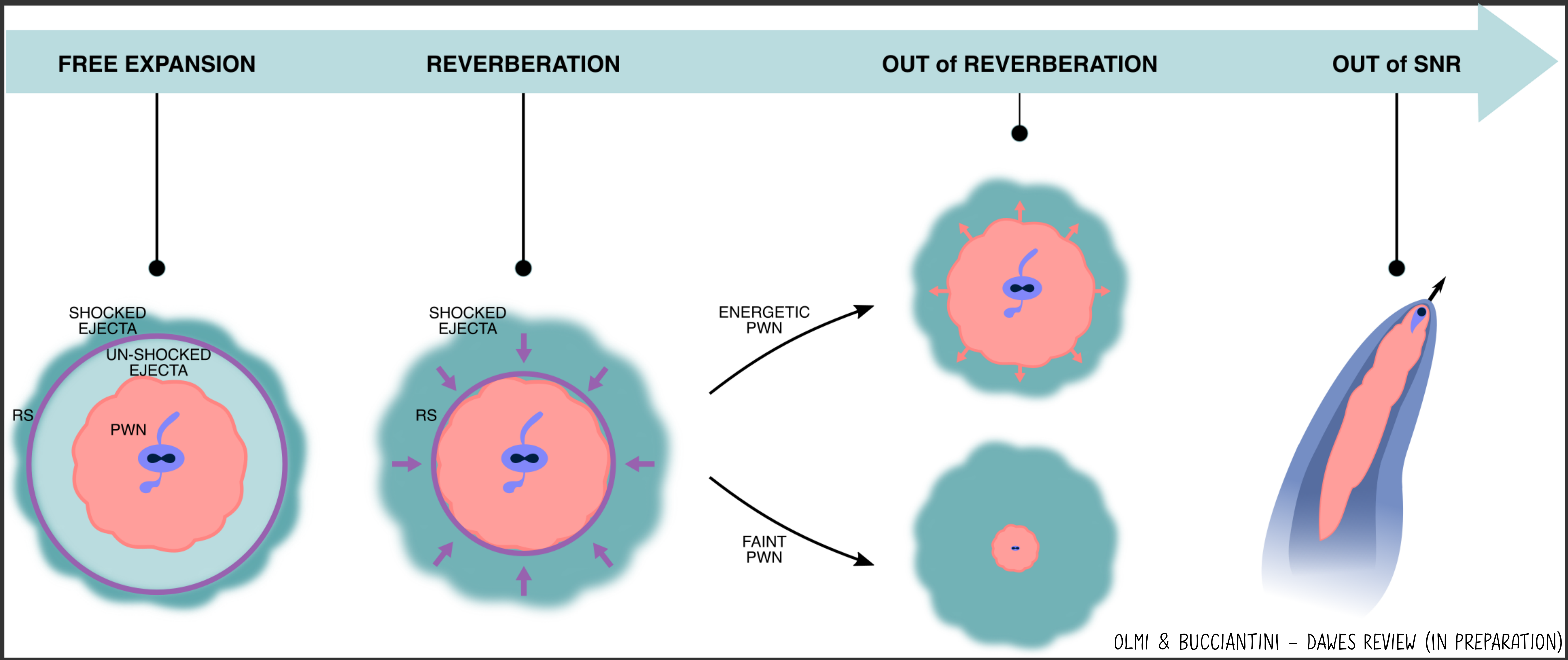
MODELING PWNE

THE DIFFERENT PHASES OF PWN EVOLUTION

✓ GAMMA RAYS
#1

✓ GAMMA RAYS
#2

✗ GAMMA RAYS
#3

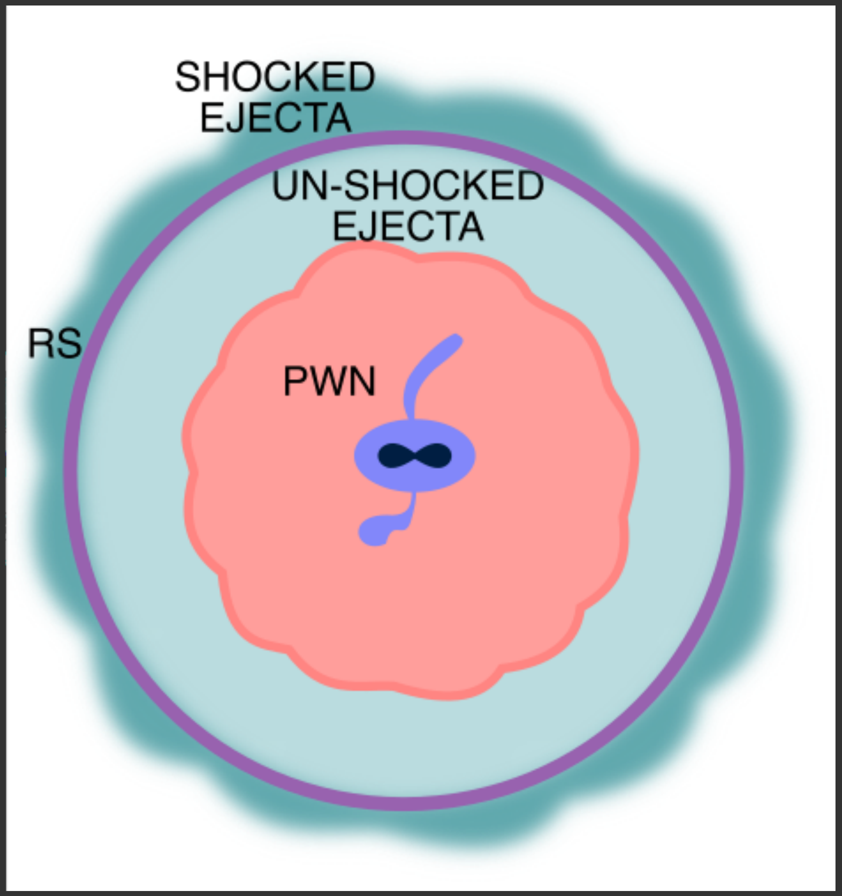


OLMI & BUCCIANTINI – DAWES REVIEW (IN PREPARATION)

EVOLVED SYSTEMS NOT DIRECTLY DETECTED AT GAMMA-RAYS SO FAR

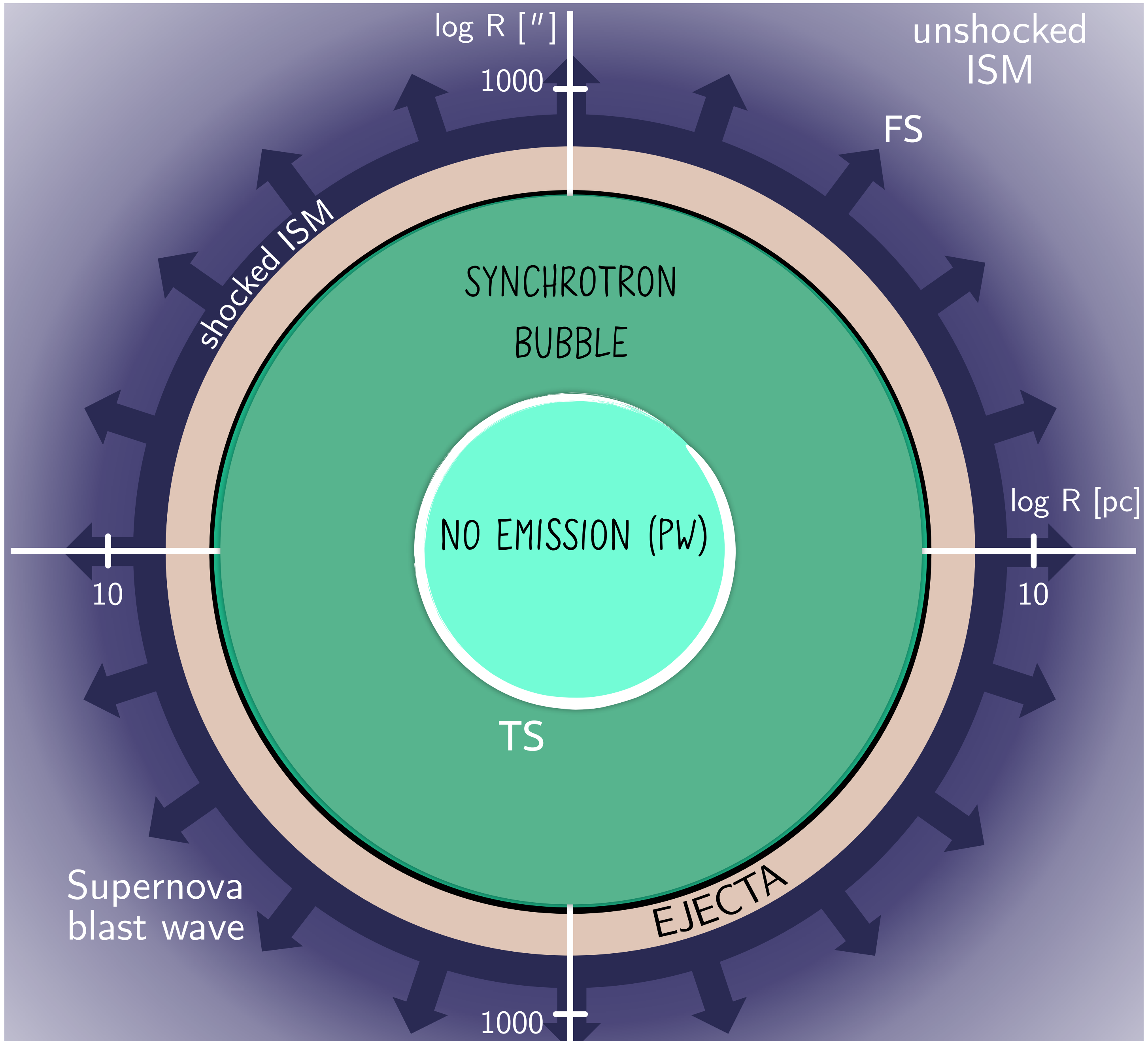
BUT CONNECTION WITH INTERESTING FEATURES (TEV HALOS + X-RAY TAILS)

#1



YOUNG SYSTEMS - FREE EXPANSION PHASE

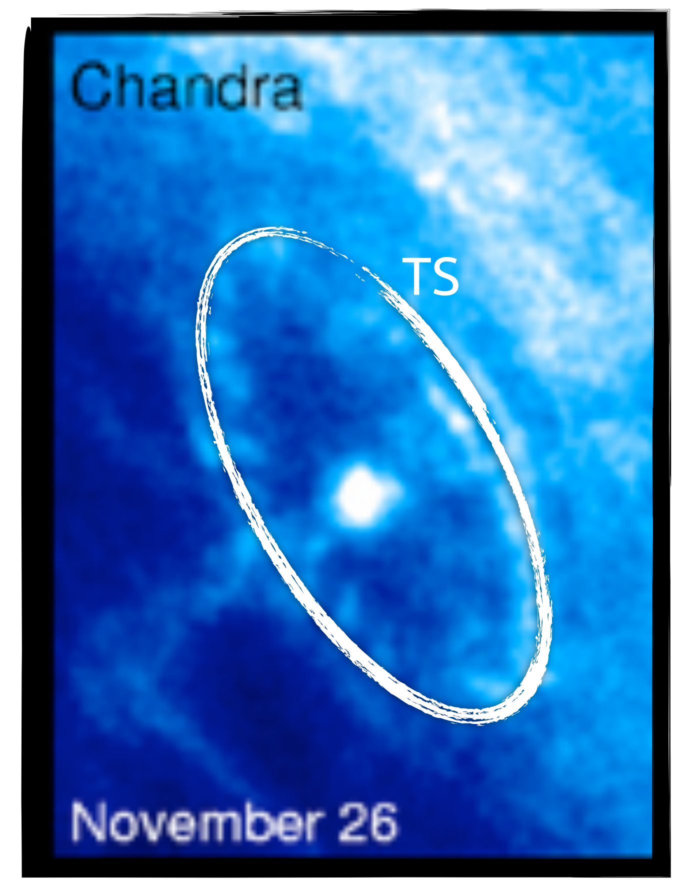
A ROUGH SUM UP



Adapted from Kennel & Coroniti 1984 [Del Zanna & Olmi 2017]

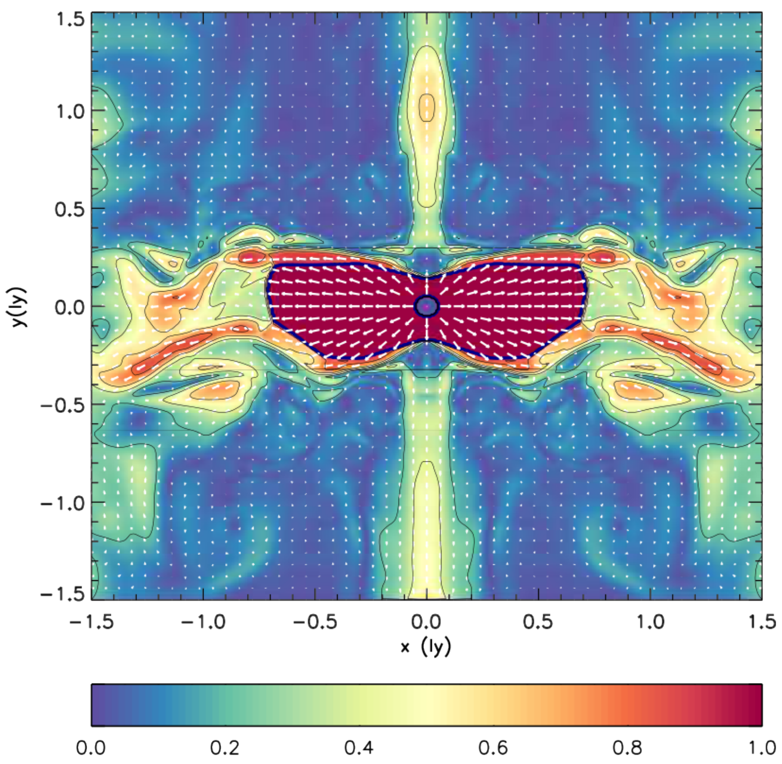
SIMPLIFIED **1D MODELS** ALREADY PREDICT A NUMBER OF FEATURES:

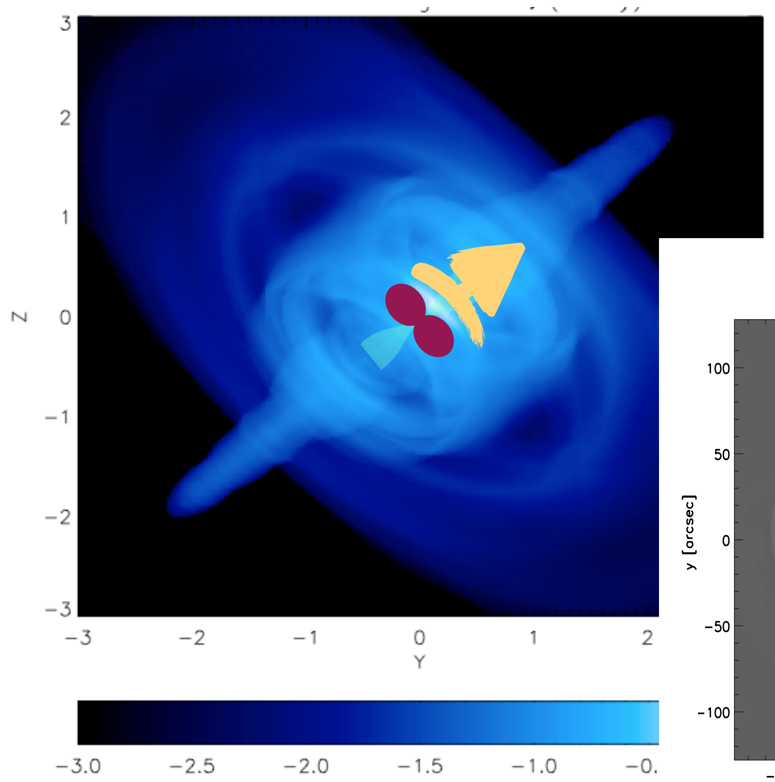
- positon of TS → $R_{TS} \sim R_N (V_N/c)^{1/2} \sim 0.1$ pc
- Optical / X-ray spectrum
- size shrinkage with increasing energy
- wind Lorentz factor ~10^6
- wind magnetization ~10^{-3}



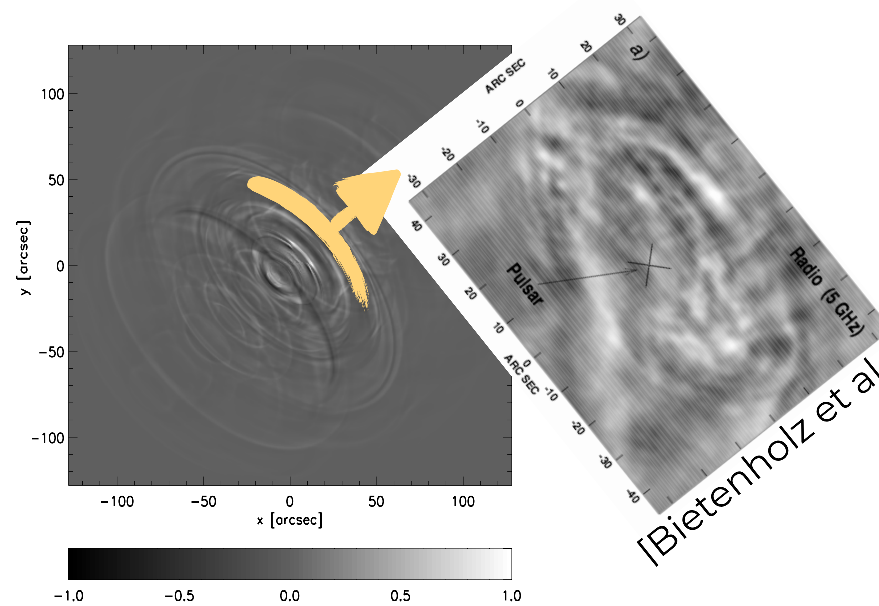
[Rees & Gunn 74, Kennel & Coroniti 84, Emmering & Chevalier 87, Begelman & Li 92,de Jager & Harding 92, Atoyan & Aharonian 96]

2D MHD MODELS REPRODUCE THE INNER NEBULA + VARIABILITY





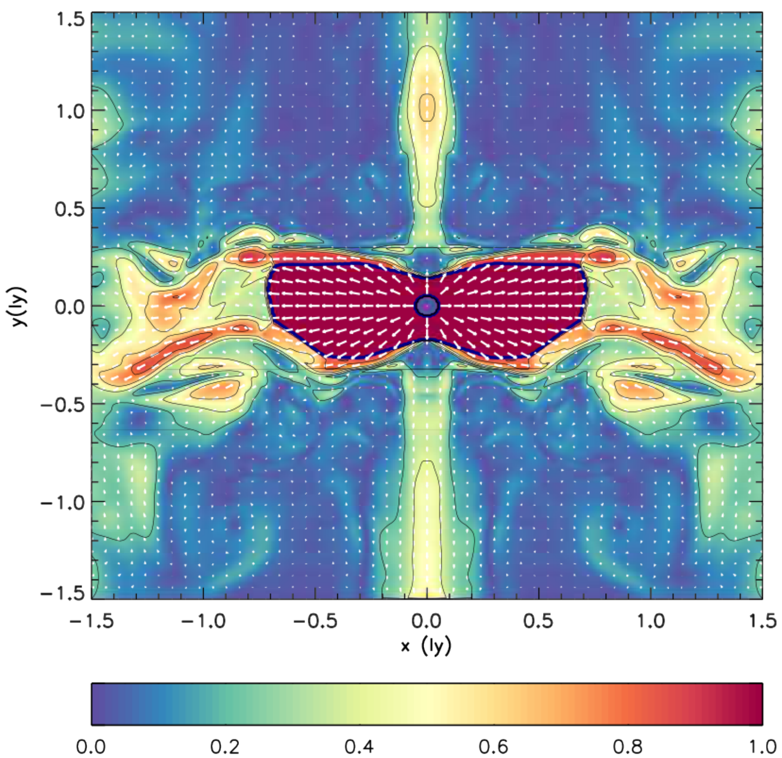
[Komissarov & Lyubarsky 2003-2004, Del Zanna et al. 2004]

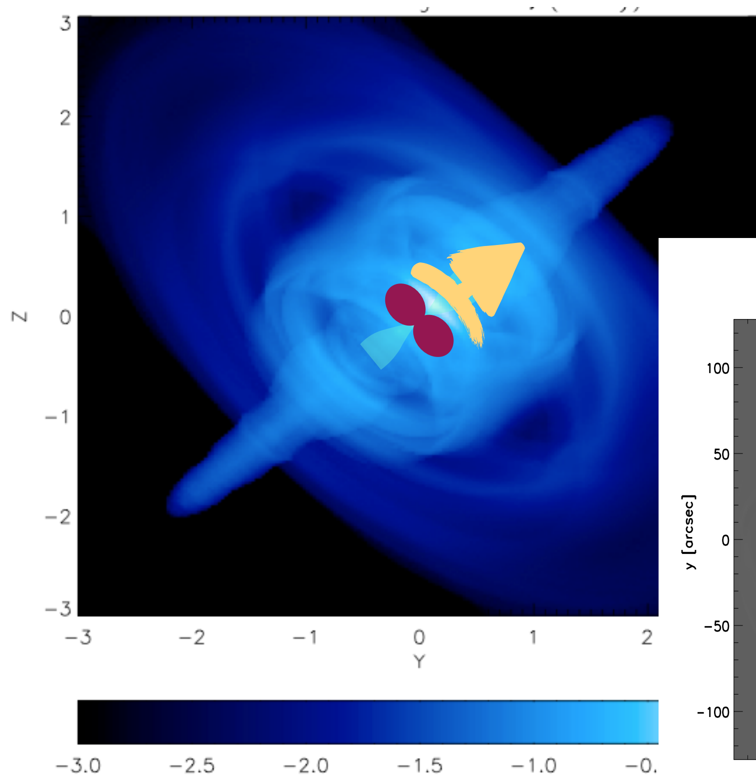


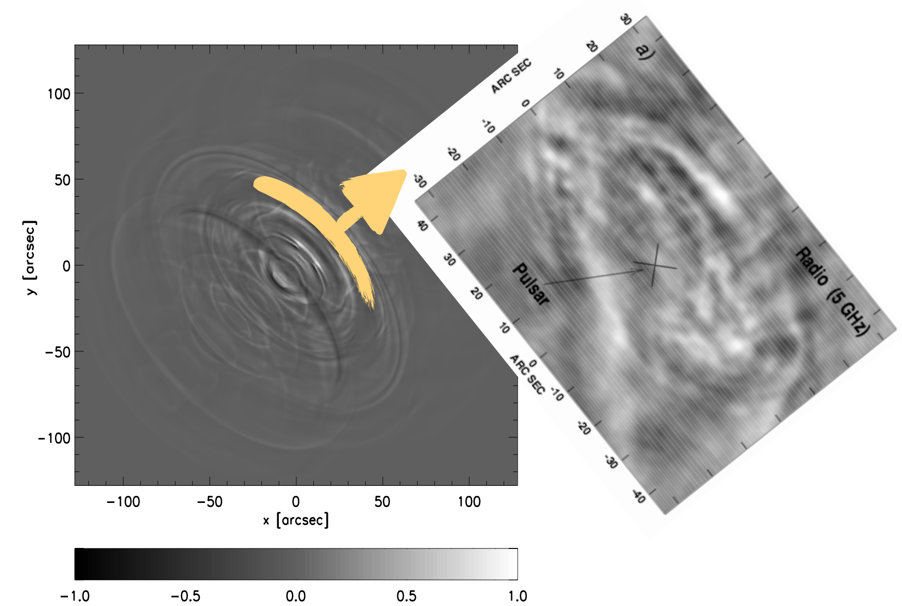
[Bietenholz et al. 01]

CRAB WISPs
[Camus et al 2009,Olmi et al. 2014]

A ROUGH SUM UP

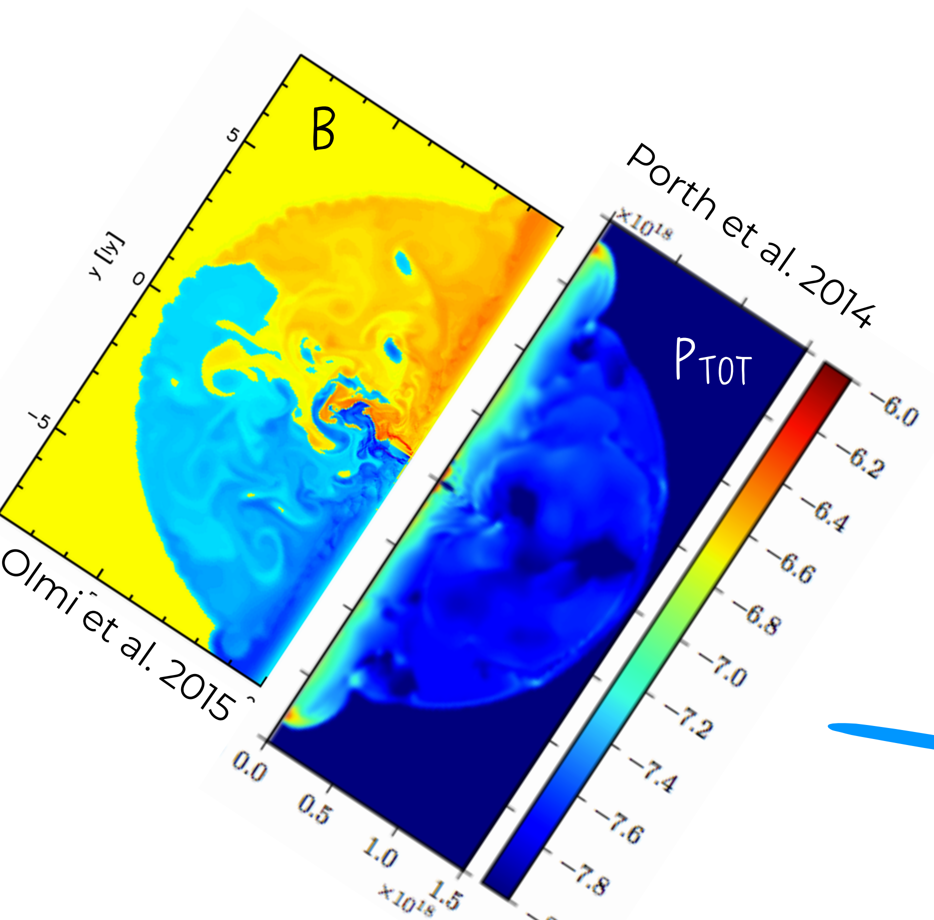




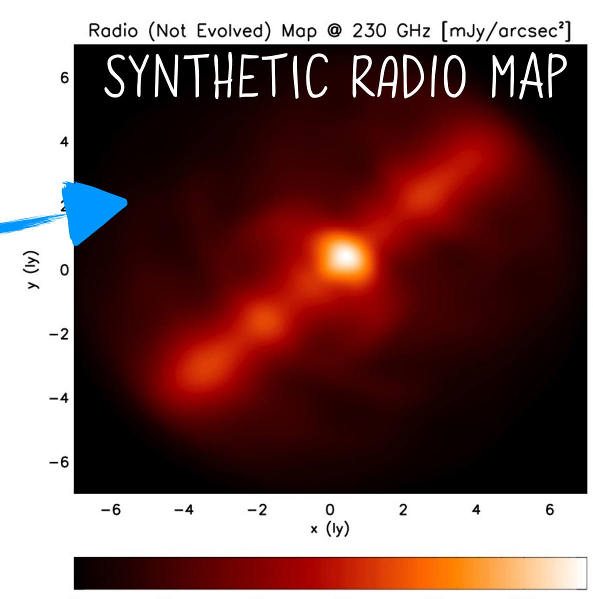


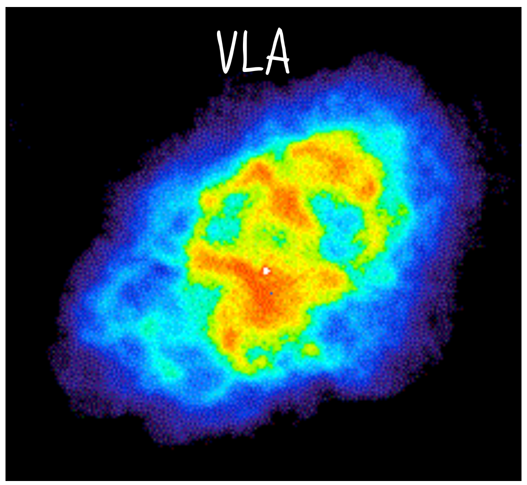
2D MHD MODELS REPRODUCE THE INNER NEBULA + VARIABILITY

BUT FAILS IN REPRODUCING THE MAGNETIC FIELD



WRONG GLOBAL MORPHOLOGY

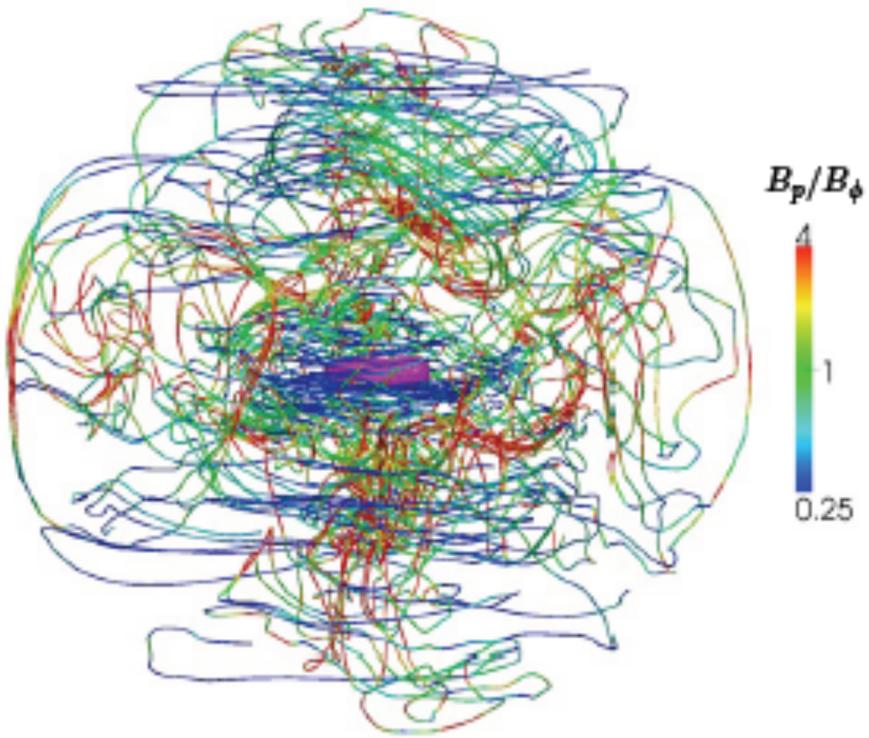




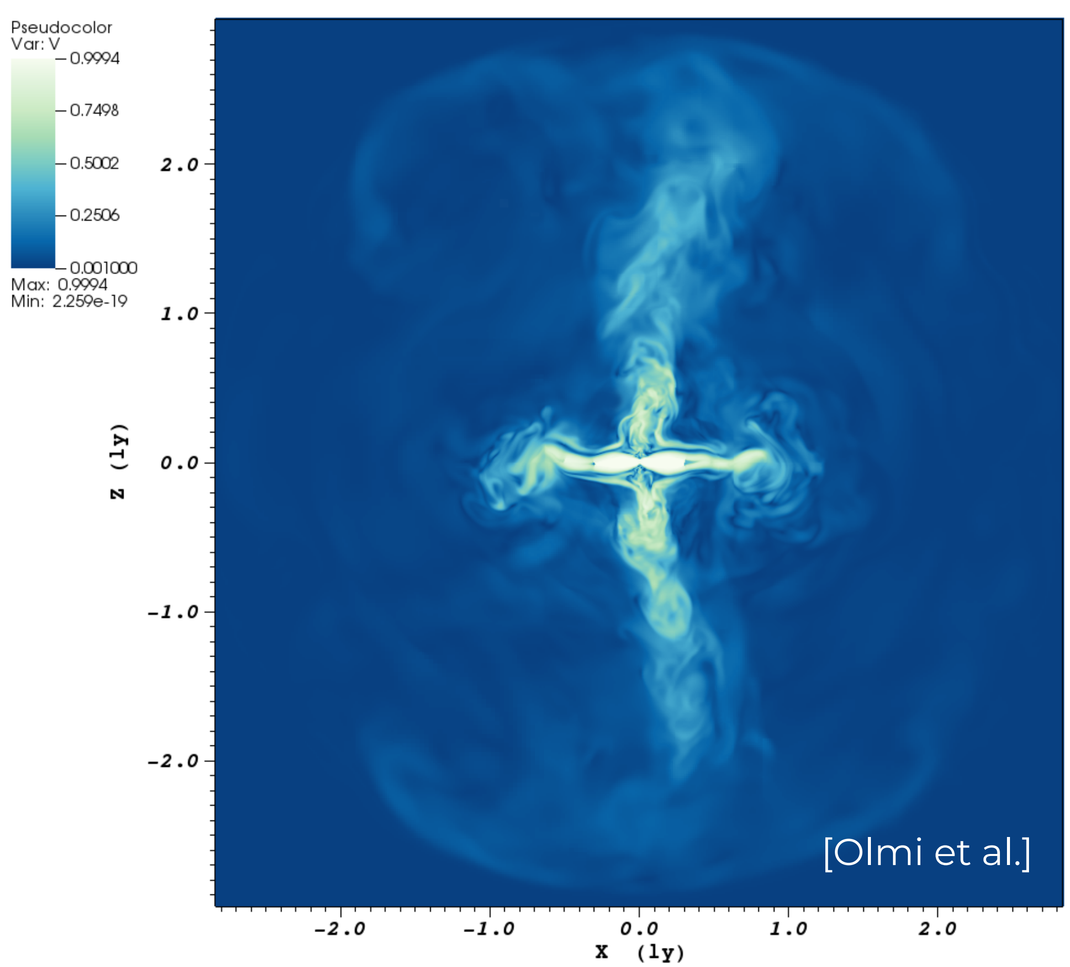
TOO LOW ENERGY LOSSES

X-RAY SPECTRUM NOT REPRODUCED + IC OVERESTIMATED [Volpi et al. 2008]

A ROUGH SUM UP



[Porth et al. 2013-2014]



[Olmi et al.]

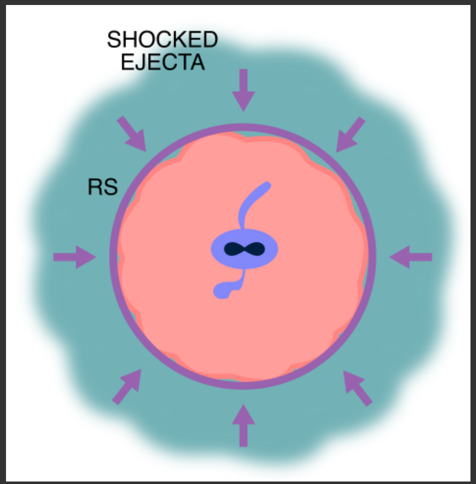
3D MHD MODELS CORRECTLY REPRODUCE THE FIELD STRUCTURE:

- DEVELOPMENT OF POLOIDAL COMPONENT
- HIGH MAGNETIC DISSIPATION ALLOW FOR $\sigma > 1$
- KINKING JETS AND VARIABILITY

3D SIMULATIONS ARE DEMANDING (NUM RESOURCES, TIME, DATA STORAGE)

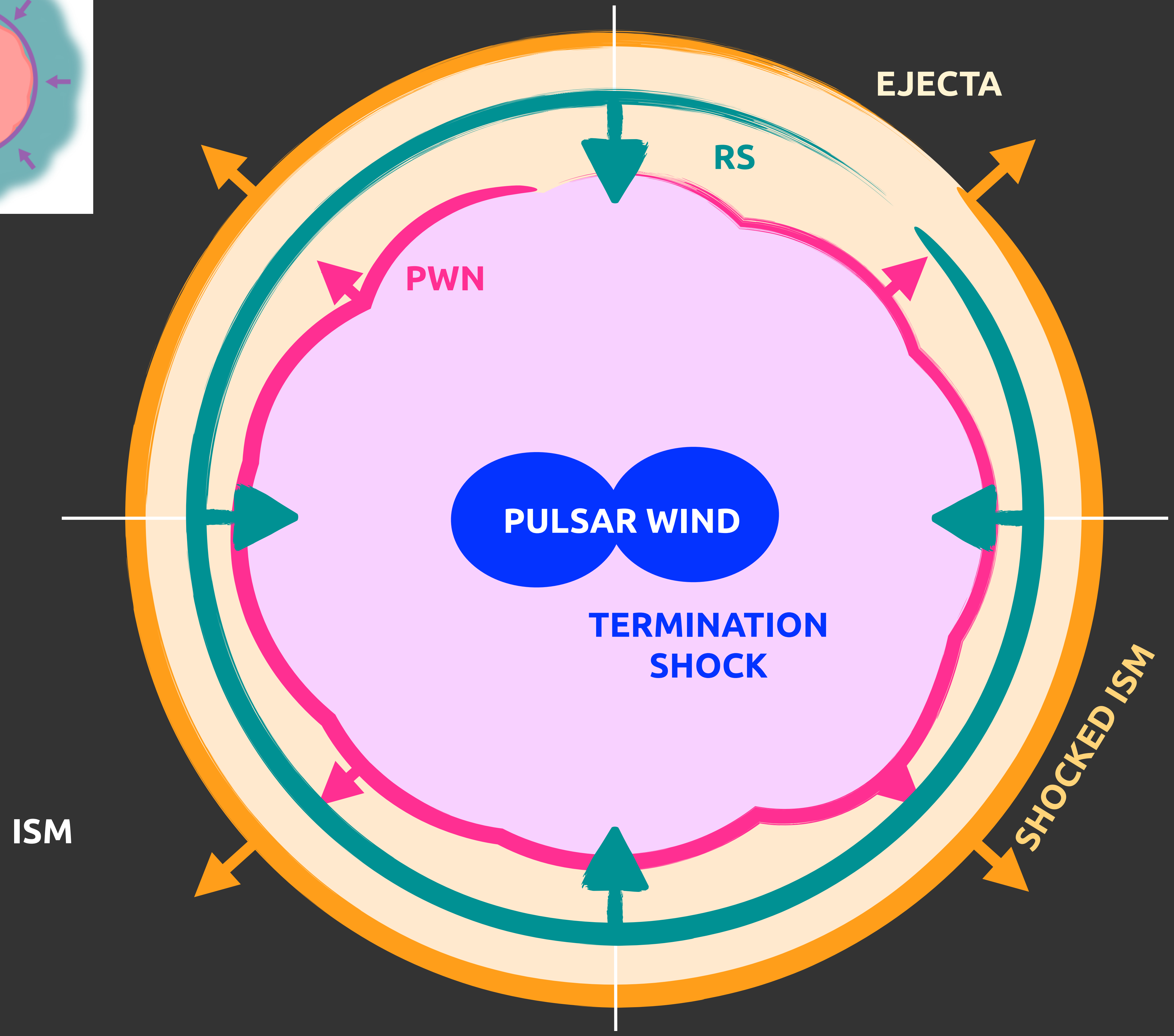
ONLY RUN FOR SELECTED OBJECTS
+ LIMITED EVOLUTION

#2



MIDDLE AGED SYSTEMS

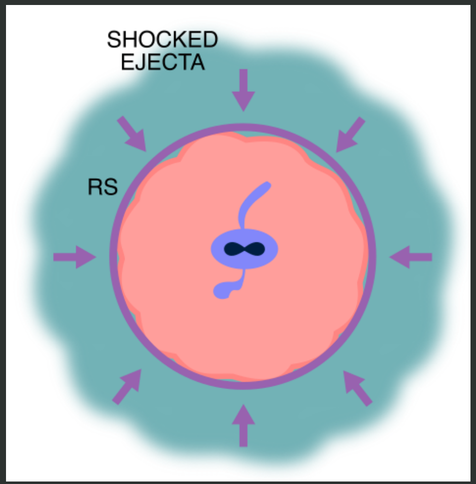
PWN/SNR INTERACTION –> REVERBERATION PHASE

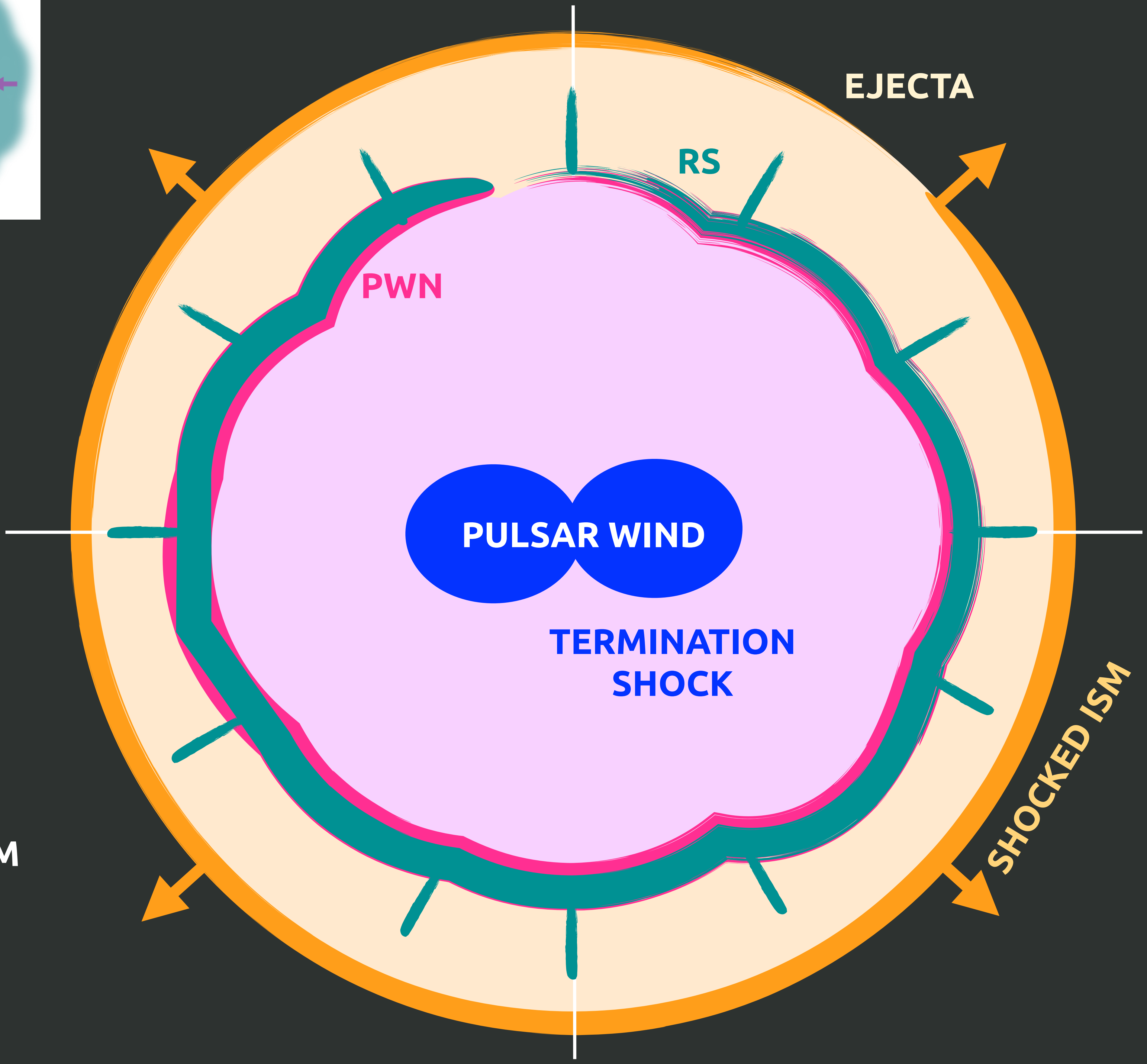


#2

MIDDLE AGED SYSTEMS

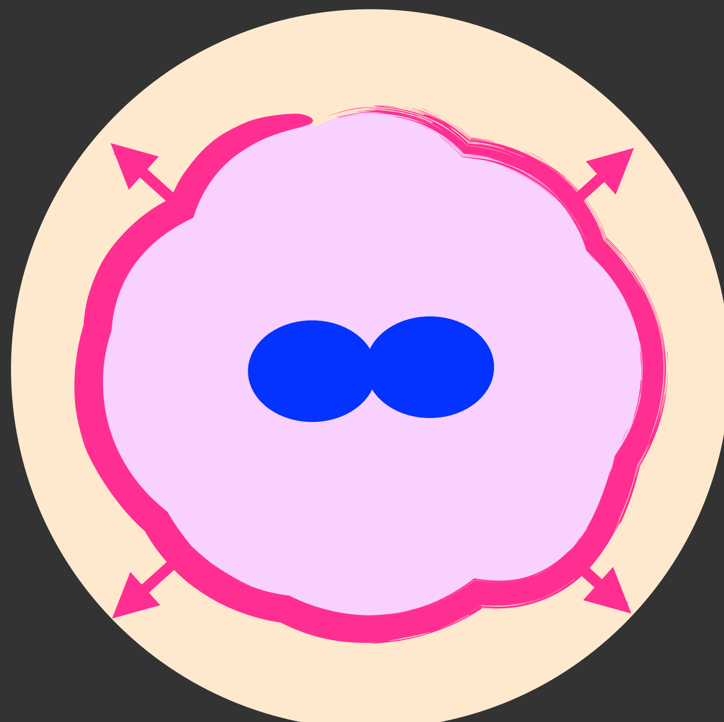
PWN/SNR INTERACTION -> REVERBERATION PHASE





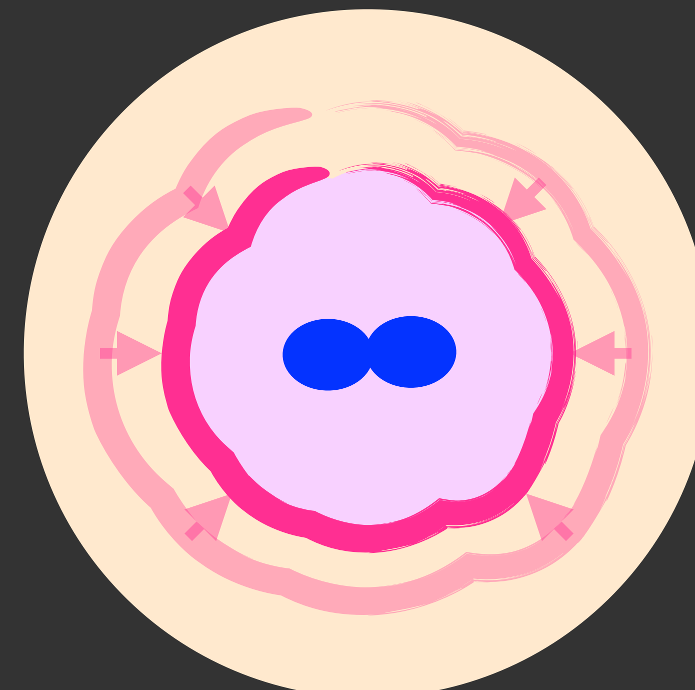
WHAT HAPPENS DURING REVERBERATION?

POWERFUL PWN

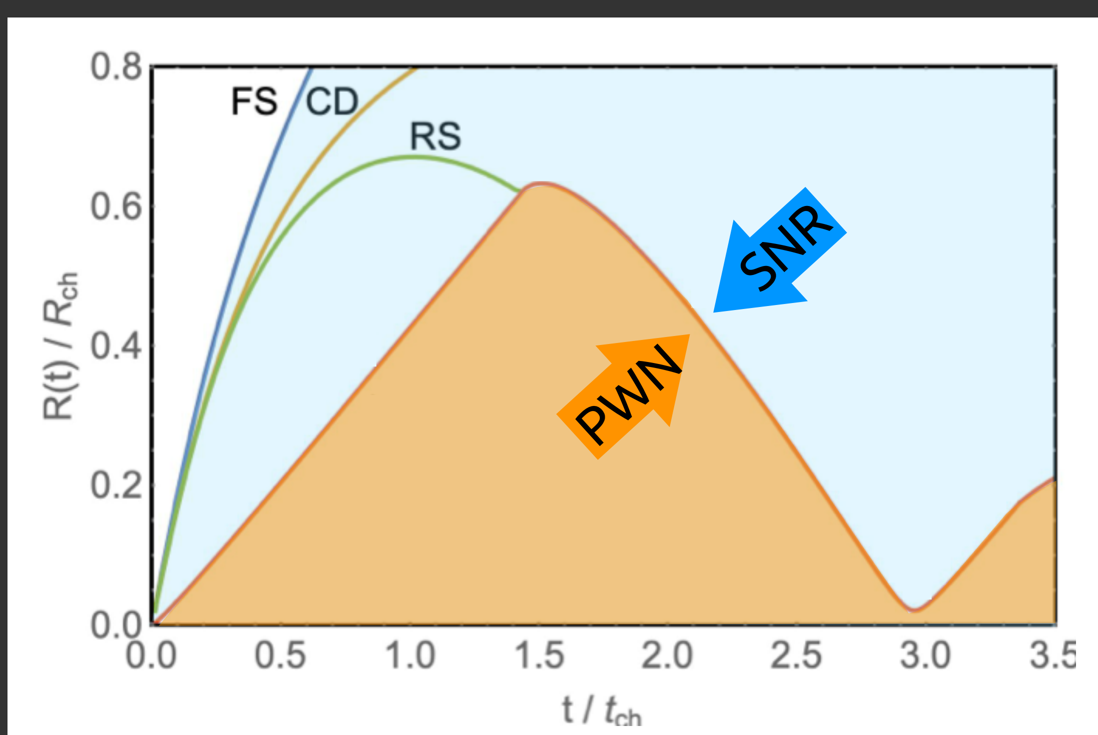


~NO COMPRESSION

FAINT PWN



COMPRESSION (EVEN EXTREME)



WHAT DEFINITELY SHAPES THE EVOLUTION IS THE BALANCE BETWEEN THE INTERNAL (PWN) PRESSURE AND EXTERNAL (SNR) ONE

ONE-ZONE MODELS

[Gelfand et al. 2009 - Fang & Zhang 2010 - Tanaka & Takahara 2010 - Martin et al. 2012 - Tanaka & Takahara 2013 - Vorster et al. 2013 - Torres et al. 2013-2014- 2017-2018-2019 - Gelfand et a. 2015-2017 - Bandiera et al. 2021 - Fiori et al. 2022]

FOR MORE DETAILS: J. MARTIN TALK (THIS AFTERNOON)

ASSUMPTIONS:

(1) PWN = UNIFORM BUBBLE OF LEPTONS AND MAGNETIC FIELD

(2) SHELL @ PWN BOUNDARY OF SWEPT UP MATERIAL = THIN ($R_{SHELL}=R_{PWN}$)

(3) PRESSURE OUTSIDE PWN = PRESSURE AT FS IN SEDOV SOLUTION $P_{\rm Sedov} = 0.1592 \left(\frac{t}{t_{\rm ch}}\right)^{-6/5} \frac{\rho_{\rm ISM} E_{\rm sn}}{M_{\rm ej}}$

EQUATIONS FOR THE EVOLUTION:

1. conservation of shell mass

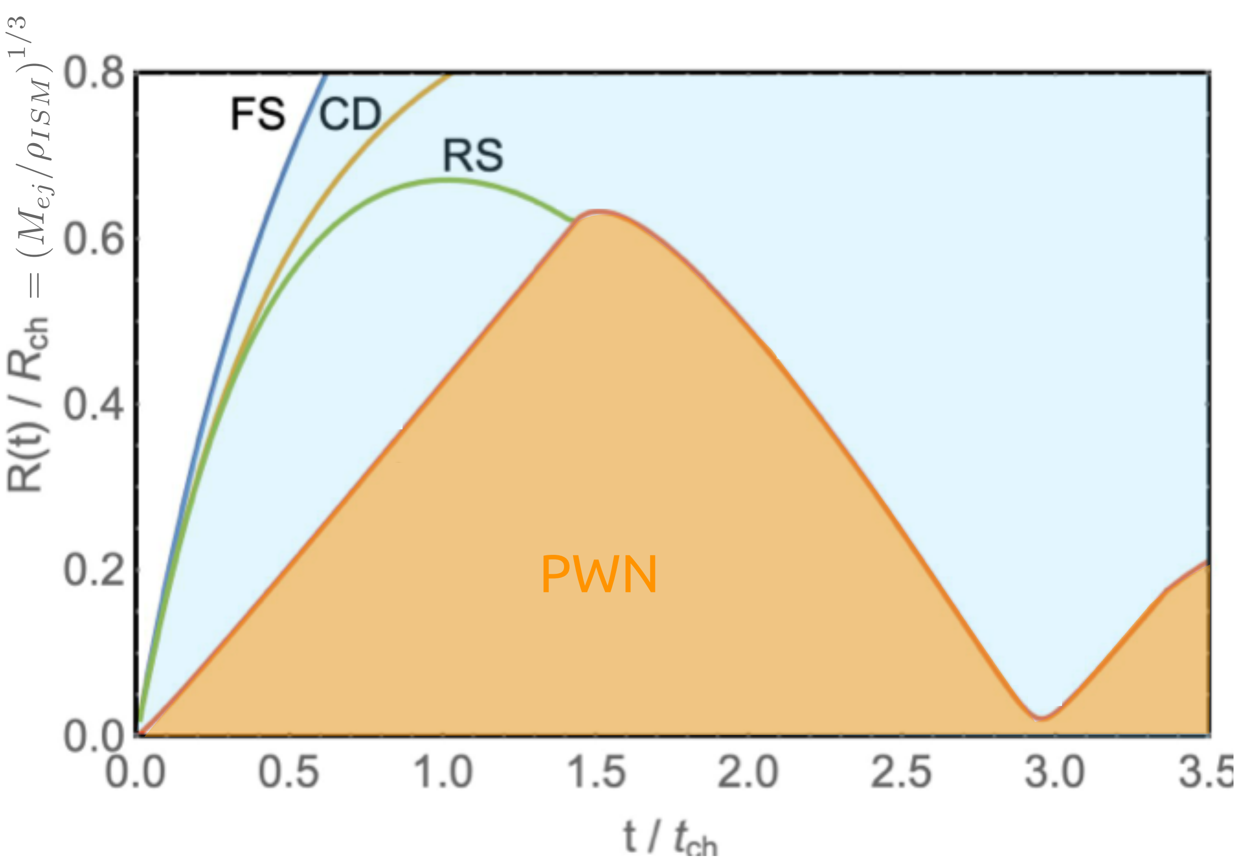
$$\frac{dM(t)}{dt} = 4\pi R^2 \rho_{\rm ej}(R,t)\left[\frac{dR}{dt} - v_{\rm ej}(R,t)\right]$$

2. conservation of shell momentum

$$\frac{d}{dt}(M(t)v(t)) = 4\pi R^2\left[P_{\rm PWN}(t) - P_{\rm ej}(R,t)\right] + \frac{dM(t)}{dt} v_{\rm ej}(R,t)$$

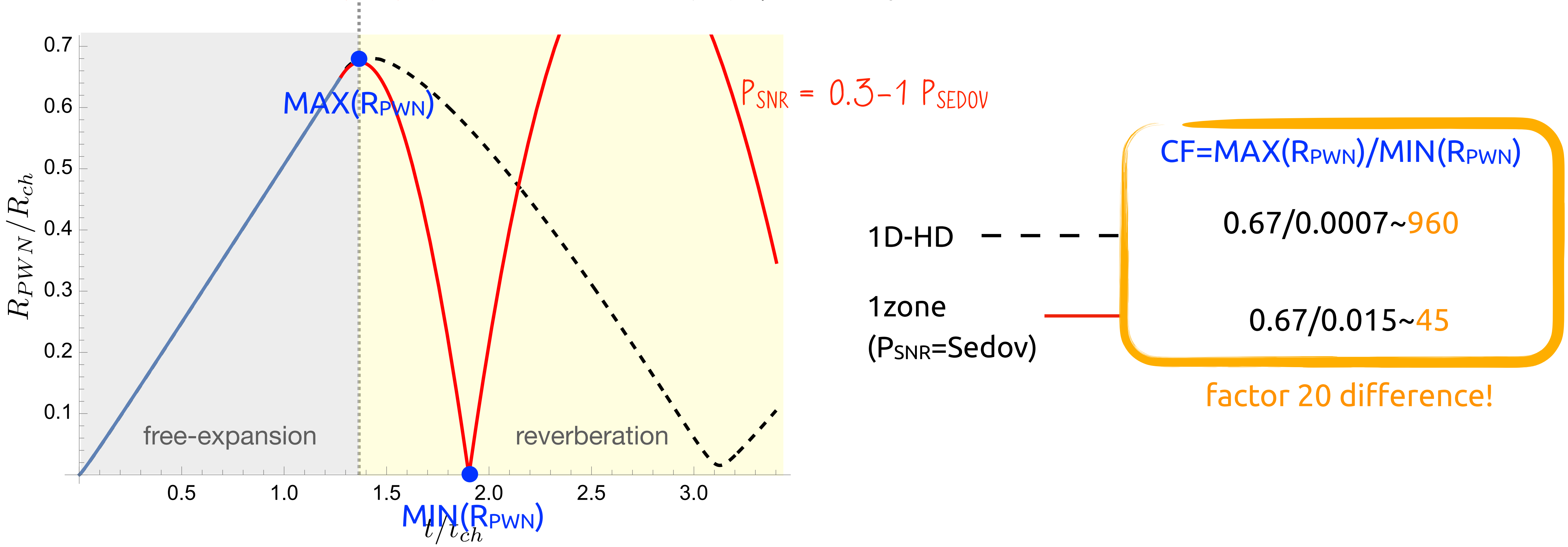
3. evolution of internal energy

$$\frac{d}{dt}\left[4\pi R^3 P_{\rm PWN}(t)\right] = L_0(1+t/\tau_0)^{-2.5} - 4\pi \frac{dR}{dt} P_{\rm PWN}(t)$$



STANDARD ONE MODELS AND THE EXTRA-COMPRESSION

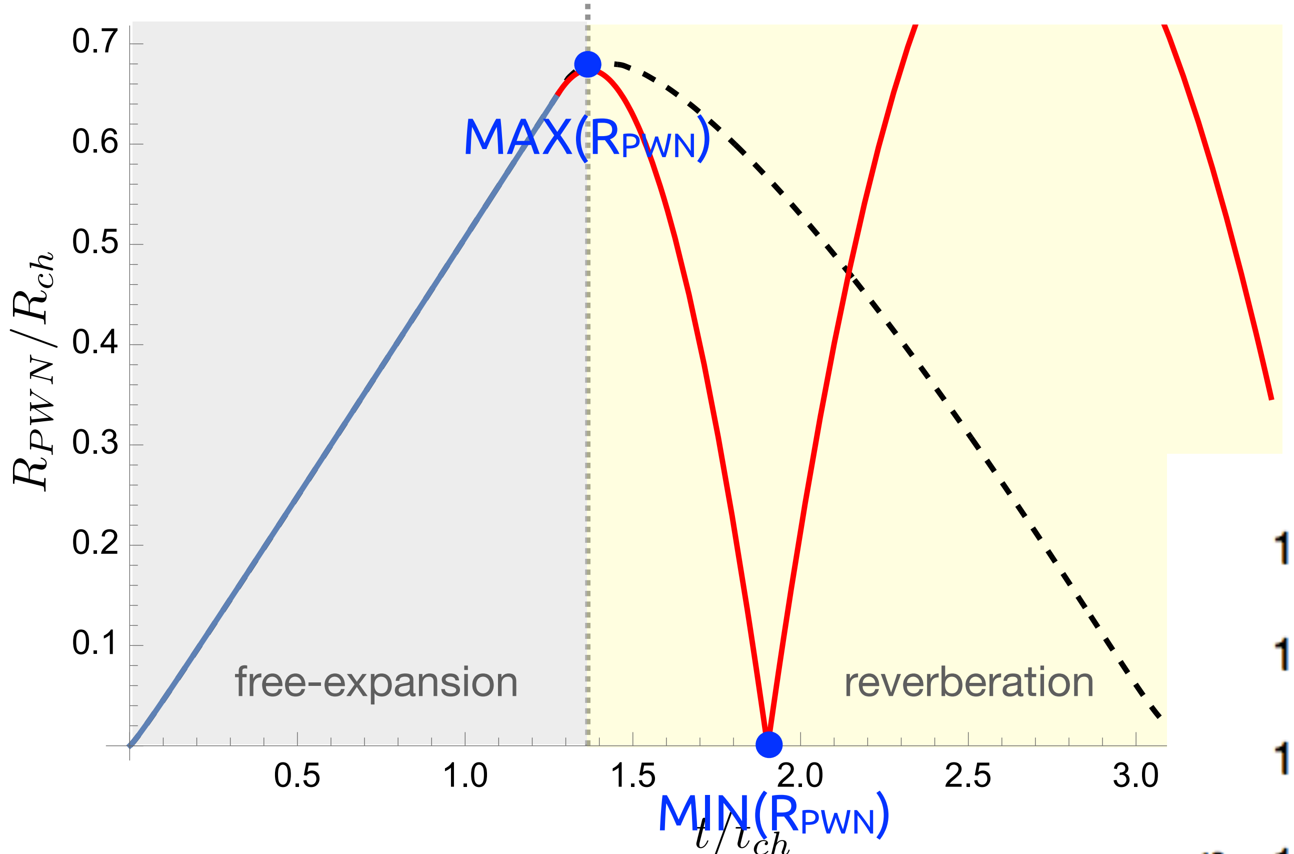
COMPARISON OF A STANDARD ONE ZONE MODEL AND 1D HD SIMULATION



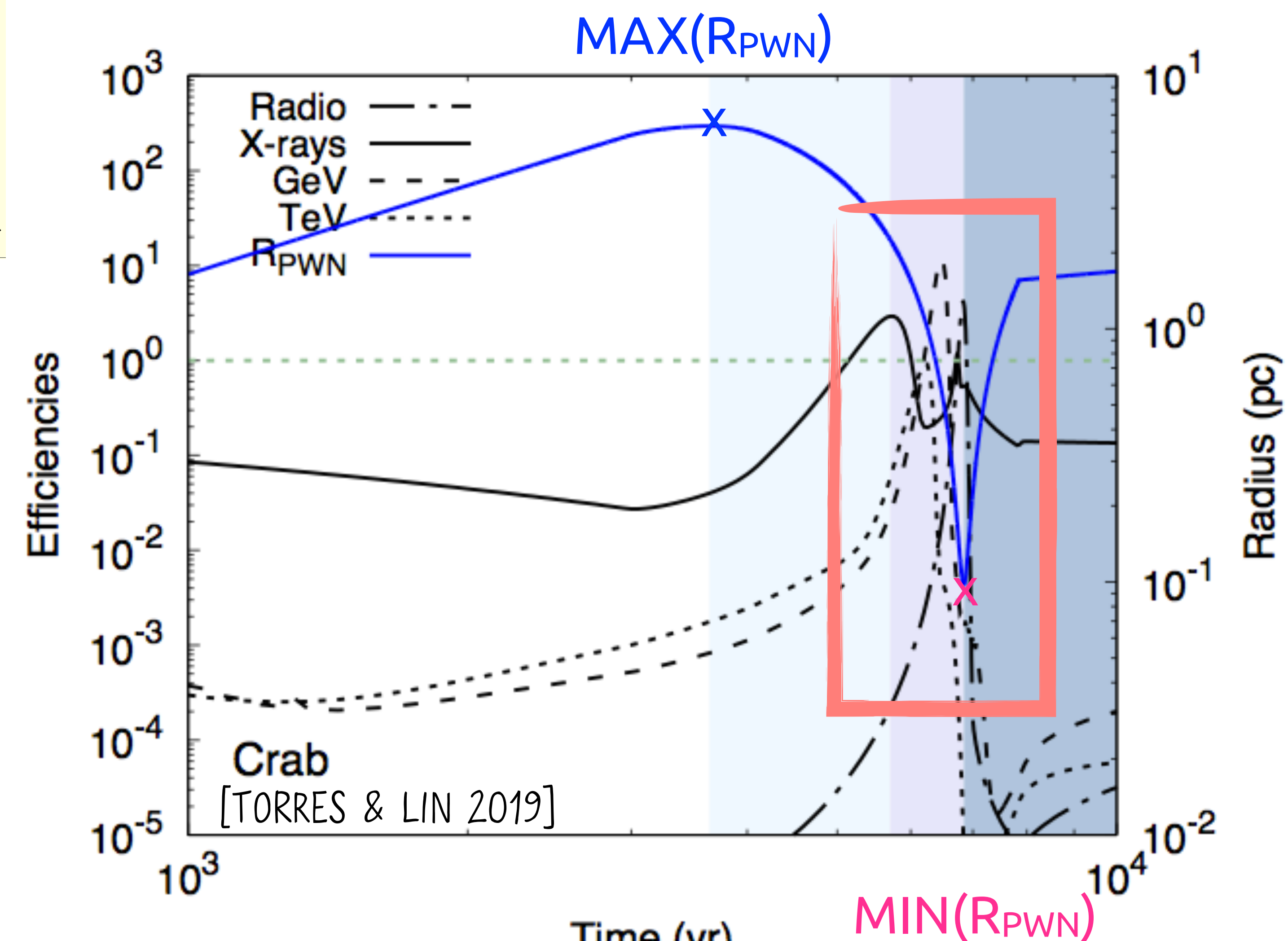
[BANDIERA ET AL. 2022, IN PREPARATION]

WHY THIS IS CRITICAL?

COMPARISON OF A STANDARD ONE ZONE MODEL AND 1D HD SIMULATION



APPEARANCE OF "SUPER-EFFICIENCY" FOR EXTREME COMPRESSIVE SYSTEMS

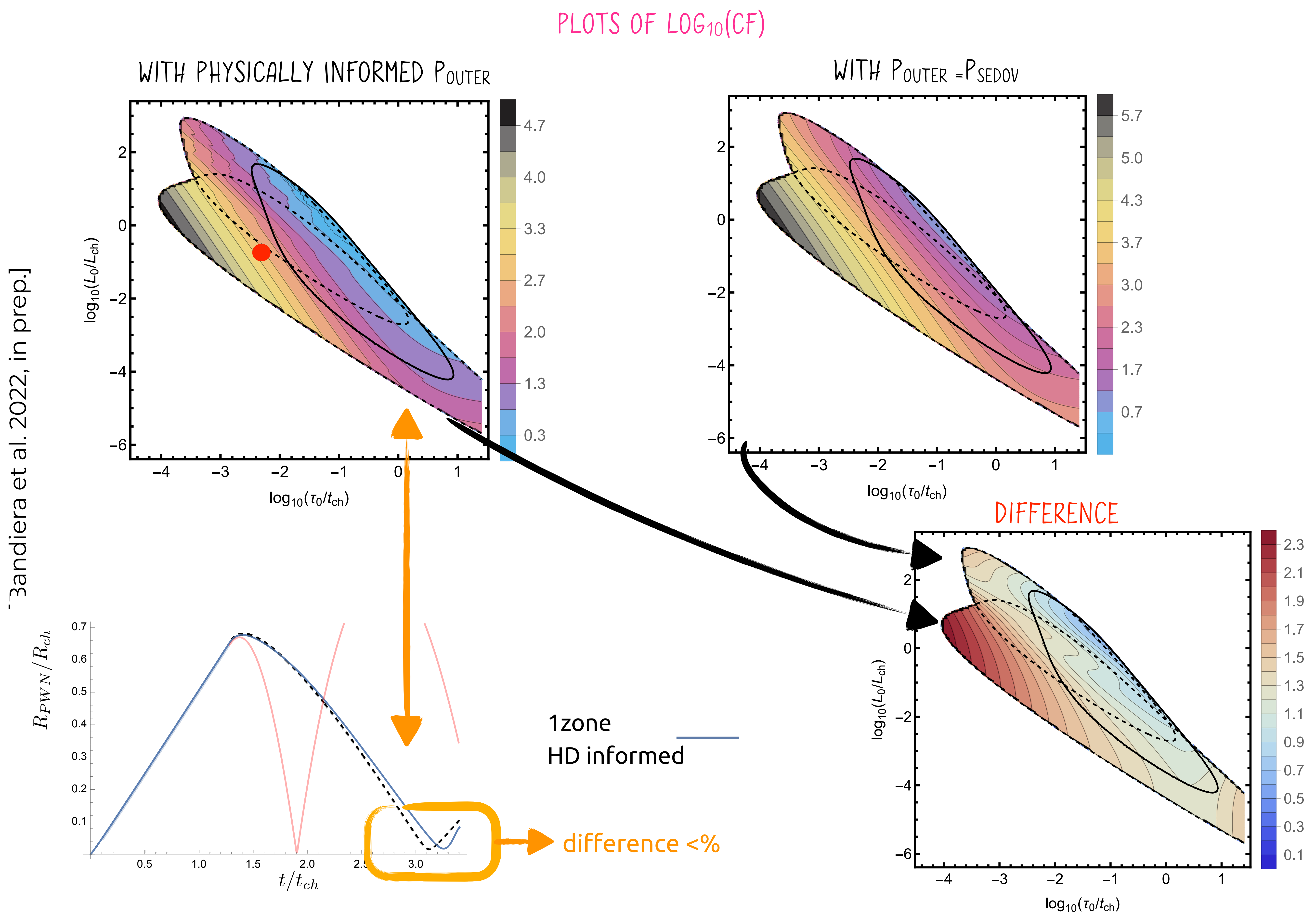


IF LARGE PART OF THE POPULATION UNDERGO SUPER-EFFICIENT PHASE, IT MIGHT DRASTICALLY CHANGE THE SED AT ALL WAVELENGTHS AND THE OUTCOME OF REVERBERATION

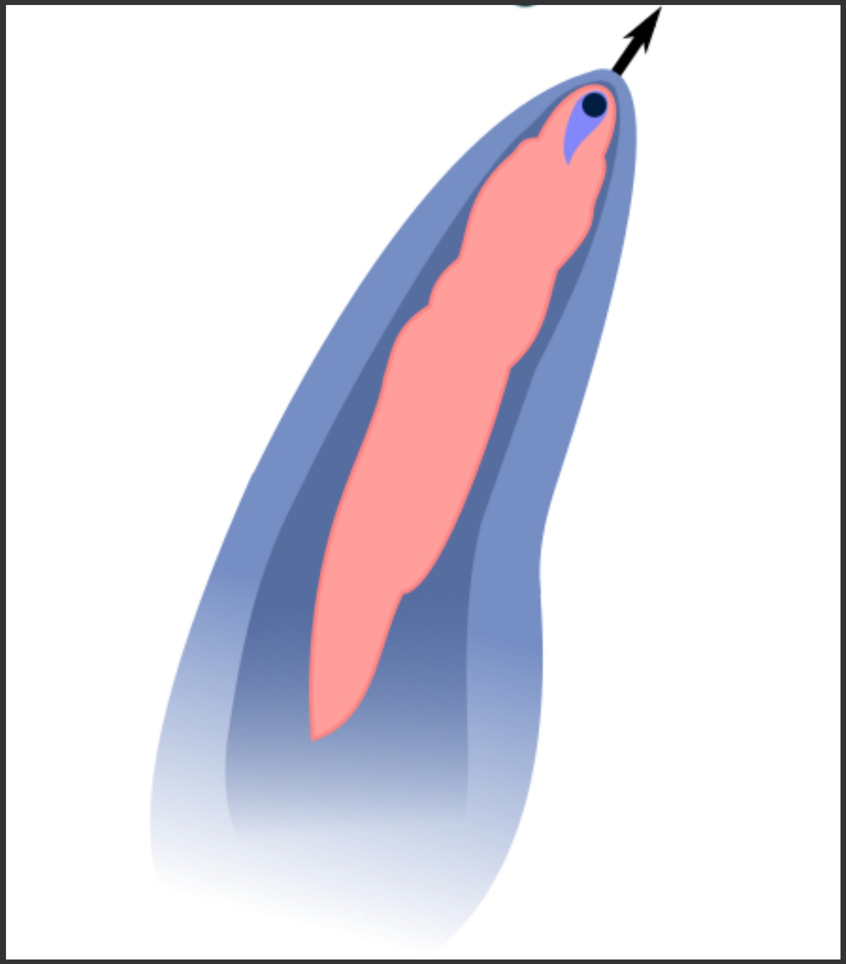
POSSIBLE BIAS IN POPULATION STUDIES!

[BANDIERA ET AL. 2022, IN PREPARATION]

STANDARD ONE MODELS AND THE EXTRA-COMPRESSION



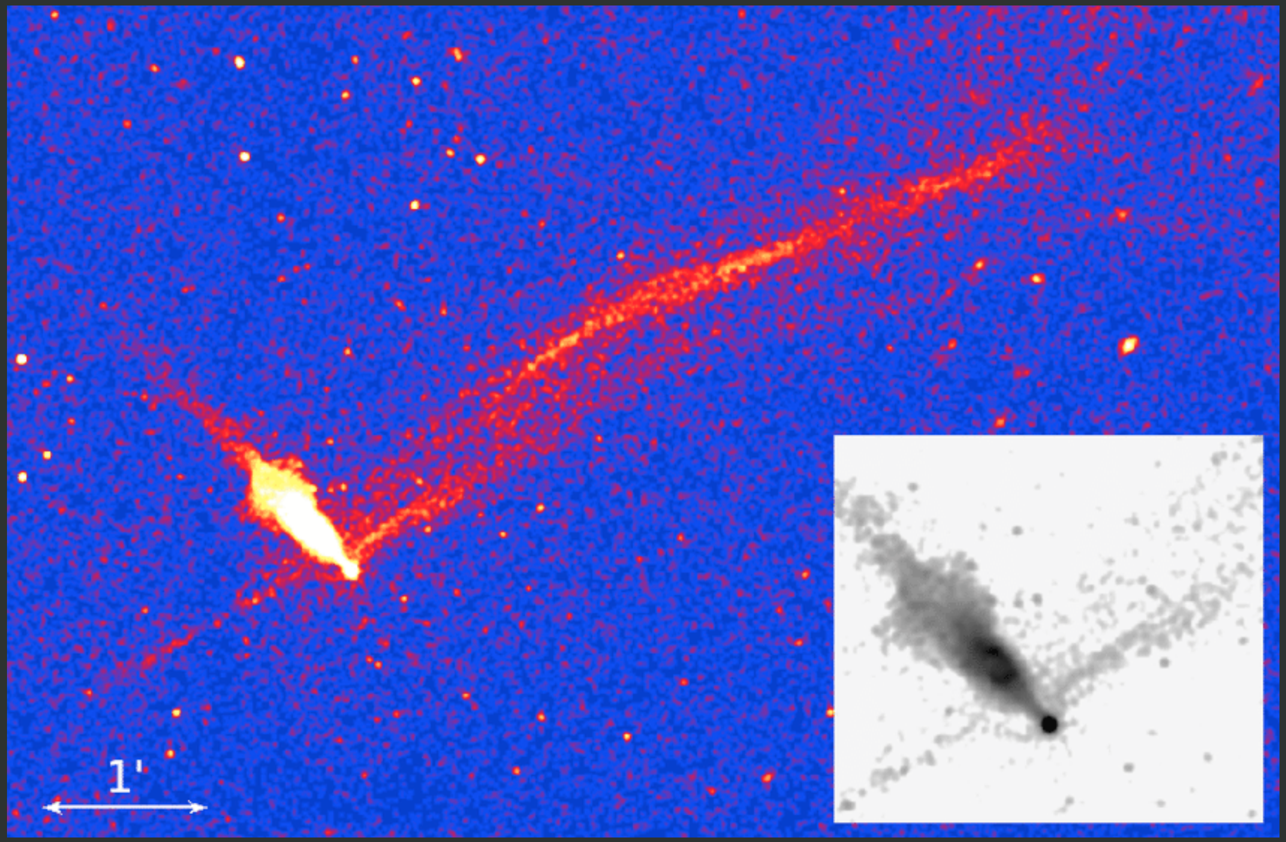
#3



OLD SYSTEMS – BOW SHOCK PHASE AND PARTICLE LEAKAGE

ESCAPE OF PARTICLES FROM BOW SHOCKS

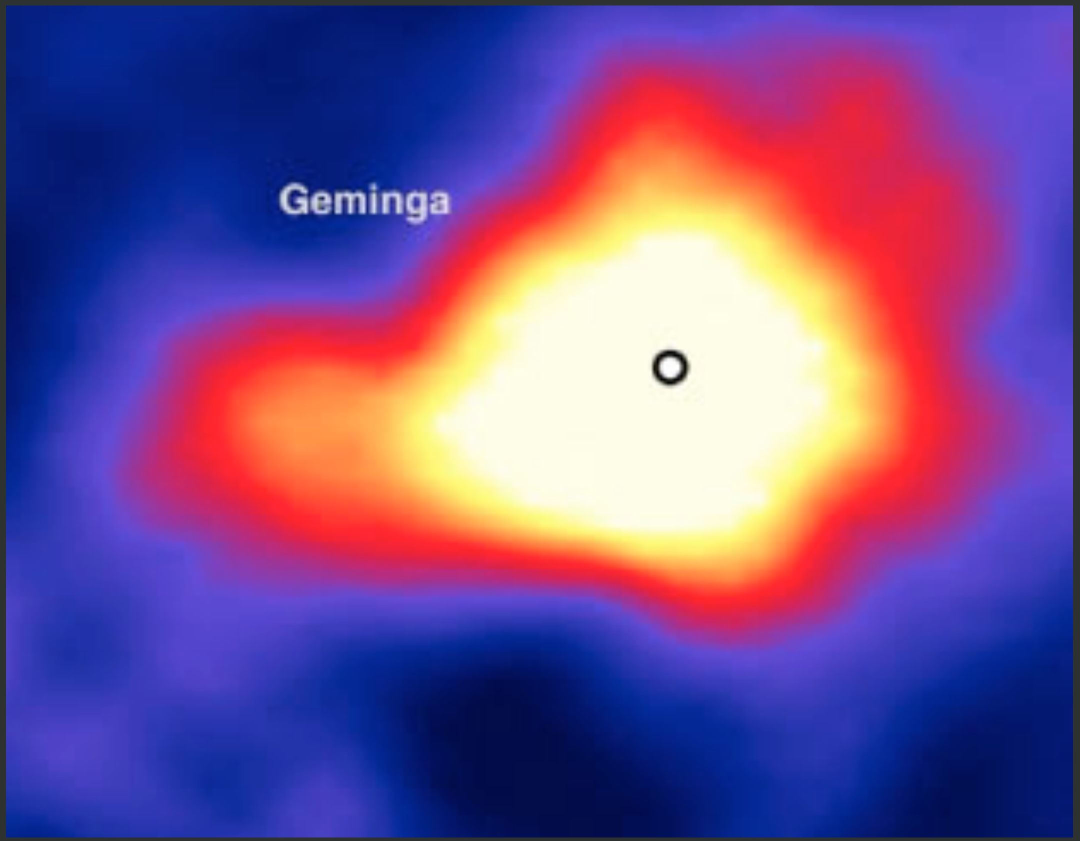
MISALIGNED X-RAY TAILS



COMPATIBLE WITH SYNCHROTRON EMISSION FROM PARTICLES WITH ENERGY CLOSE TO MAXIMUM THEORETICAL LIMIT ($E \sim e\Phi_{PSR}$) + RATHER INTENSE LOCAL FIELD (10–50 μG)

[Bandiera 2008]

TEV HALOS

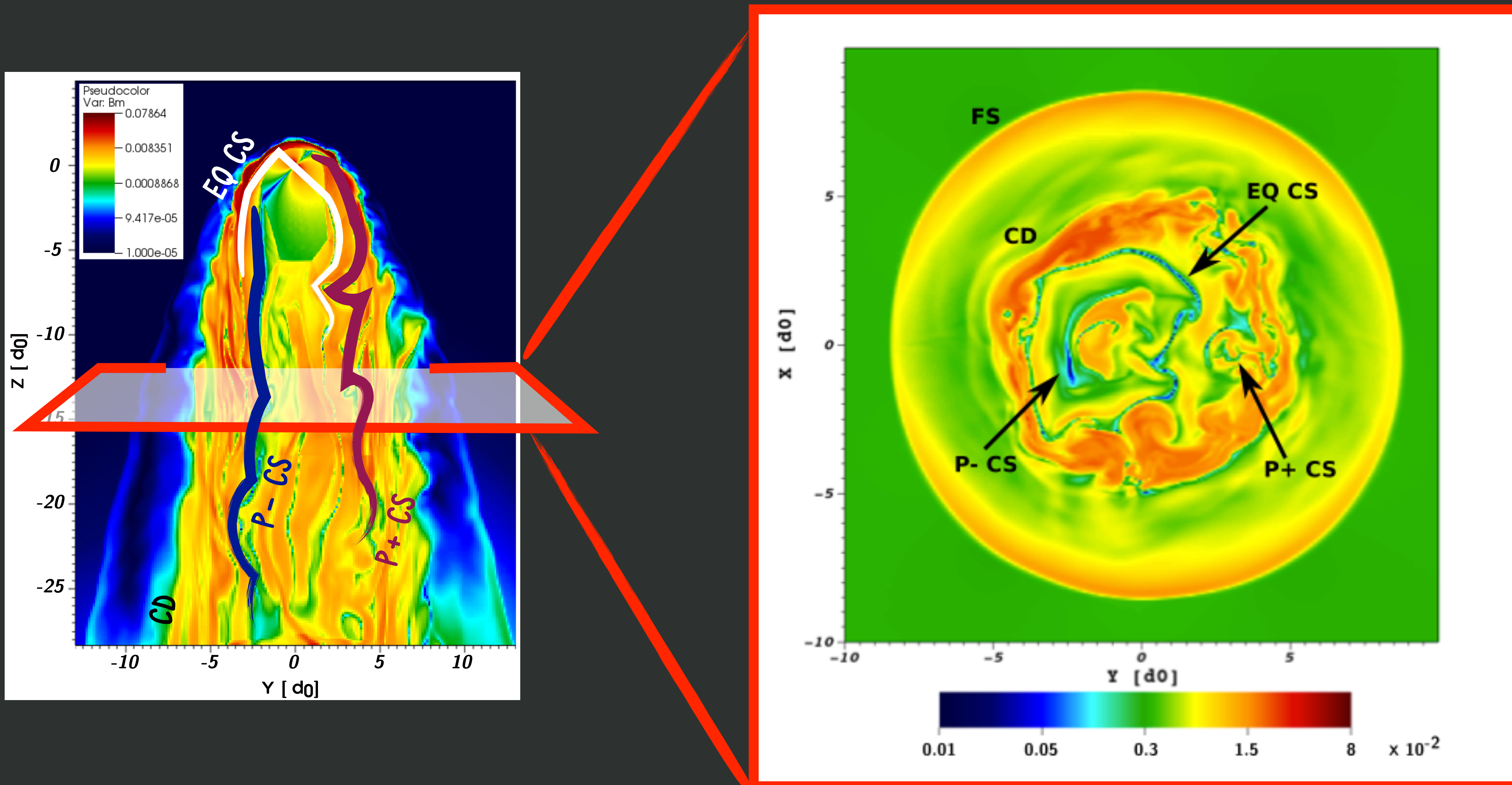


COMPATIBLE WITH ICS EMISSION FROM PARTICLES WITH ENERGY CLOSE TO MAXIMUM THEORETICAL LIMIT ($E \sim e\Phi_{PSR}$) + LOCAL FIELD (FEW μG) + REDUCED DIFFUSION COEFF. ($0.01\ D_{GAL}$)

[Abeysekara et al. 2017, Lopez-Coto & Giacinti 2018, Lopez-Coto et al 2021]

HOW CAN PARTICLE ESCAPE?

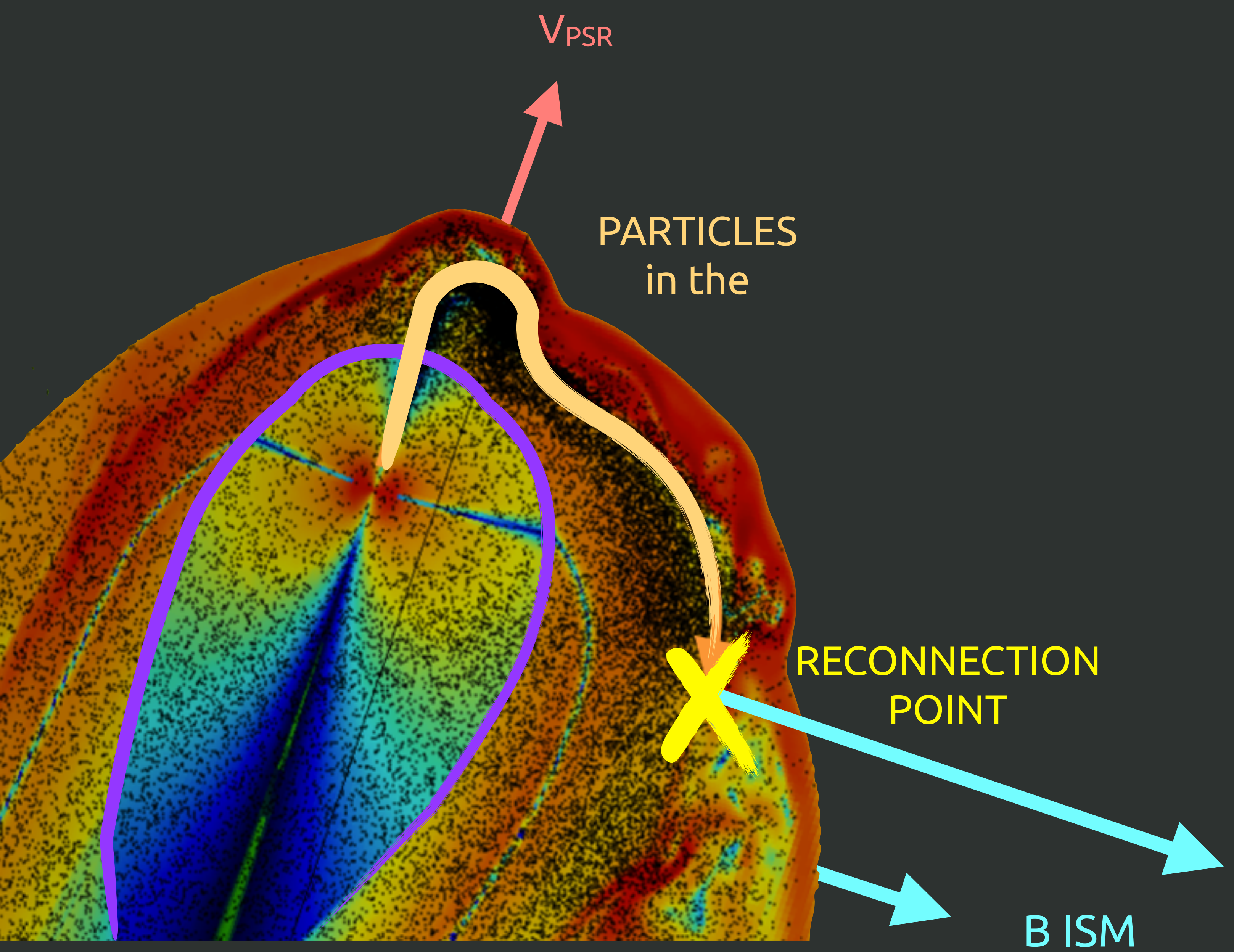
WHEN THE BS TAIL IS NOT DOMINATED BY TURBULENCE CURRENT SHEETS SURVIVE FROM INJECTION



[Barkov & Lyutikov 2018, Olmi & Bucciantini 2019c]

HOW CAN PARTICLE ESCAPE?

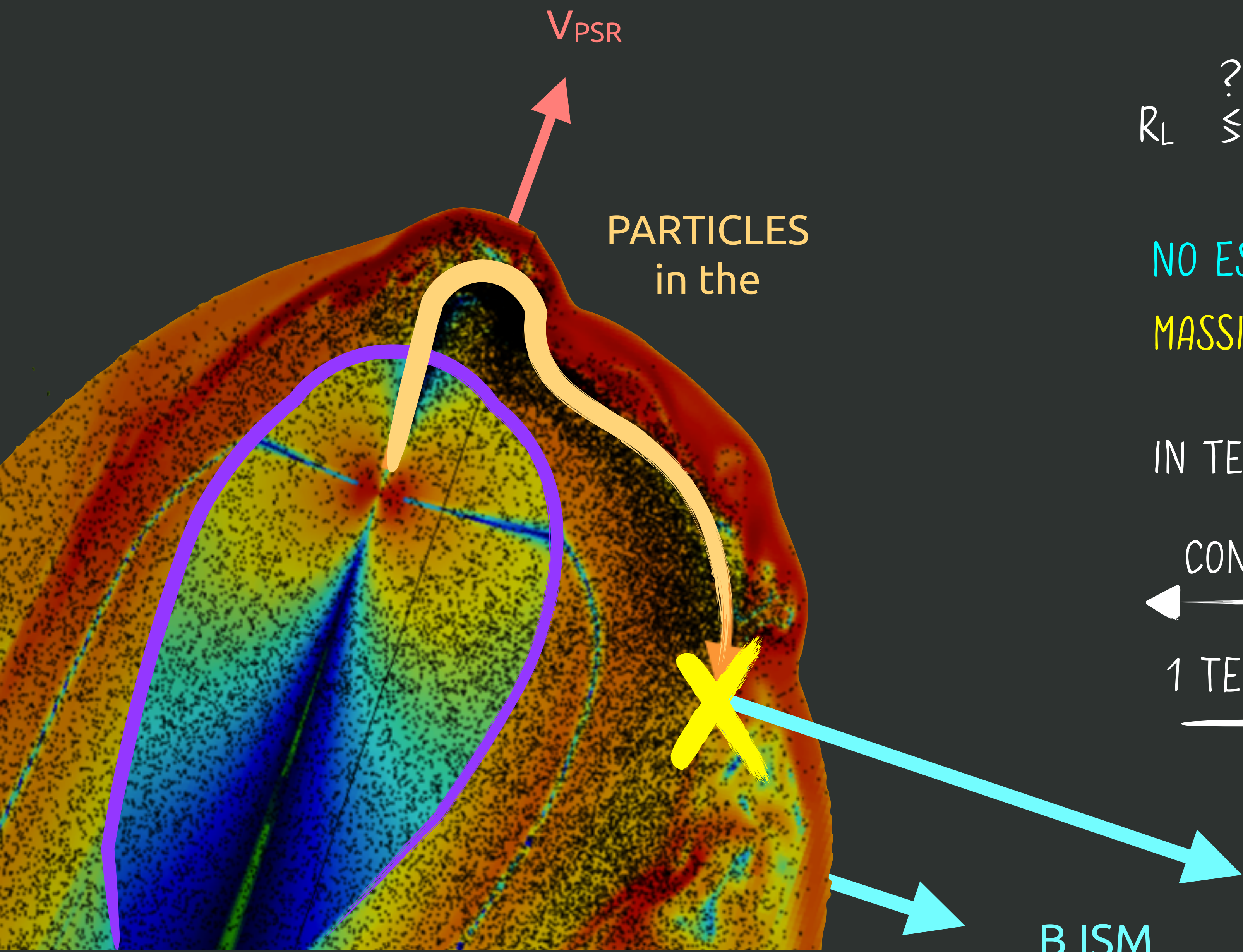
PARTICLES CONFINED IN CURRENT SHEETS FROM INJECTION
CAN ESCAPE AT RECONNECTING REGIONS AT THE MAGNETOPAUSE
THEN ON THE EXTERNAL FIELD



[Barkov et al. 2019, Bucciantini 2018, Olmi & Bucciantini 2019c]

HOW EFFICIENT IS THE PROCESS?

IT DEPENDS ON THE ENERGY (LARMOR RADIUS R_L) OF THE PARTICLES:



$$R_L \overset{?}{\lessgtr} d_0 = \sqrt{\dot{E}/(4\pi c \rho_{ISM} v_{PSR}^2)} \sim 10^{16}\,\mathrm{cm}$$

NO ESCAPE IF $R_L/D_0 \lesssim 0.1$

MASSIVE ESCAPE IF $R_L/D_0 > 0.1$

IN TERMS OF ENERGY OF ESCAPING PARTICLES:

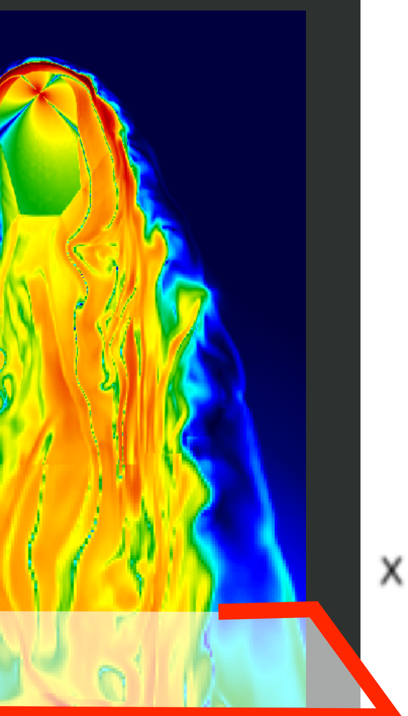
CONFINED

1 TEV — 10 TEV — 10NS OF TEV

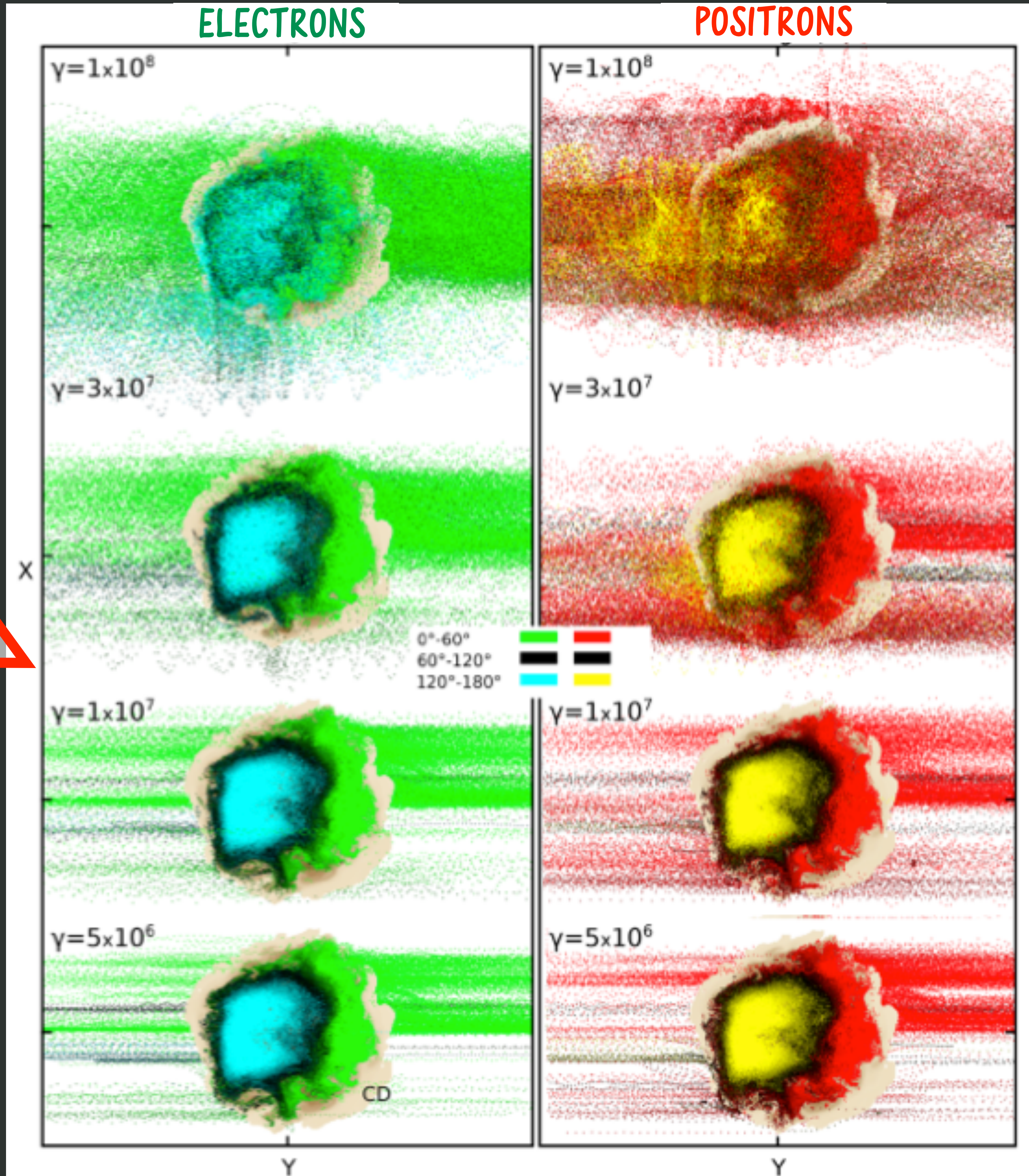
ESCAPE

[Olmi & Bucciantini 2019c]

FORMATION OF DIFFERENT STRUCTURES



VIEW FROM BACK OF THE TAIL



ENERGY

LARGER FRACTION ESCAPE - MORE ISOTROPIC

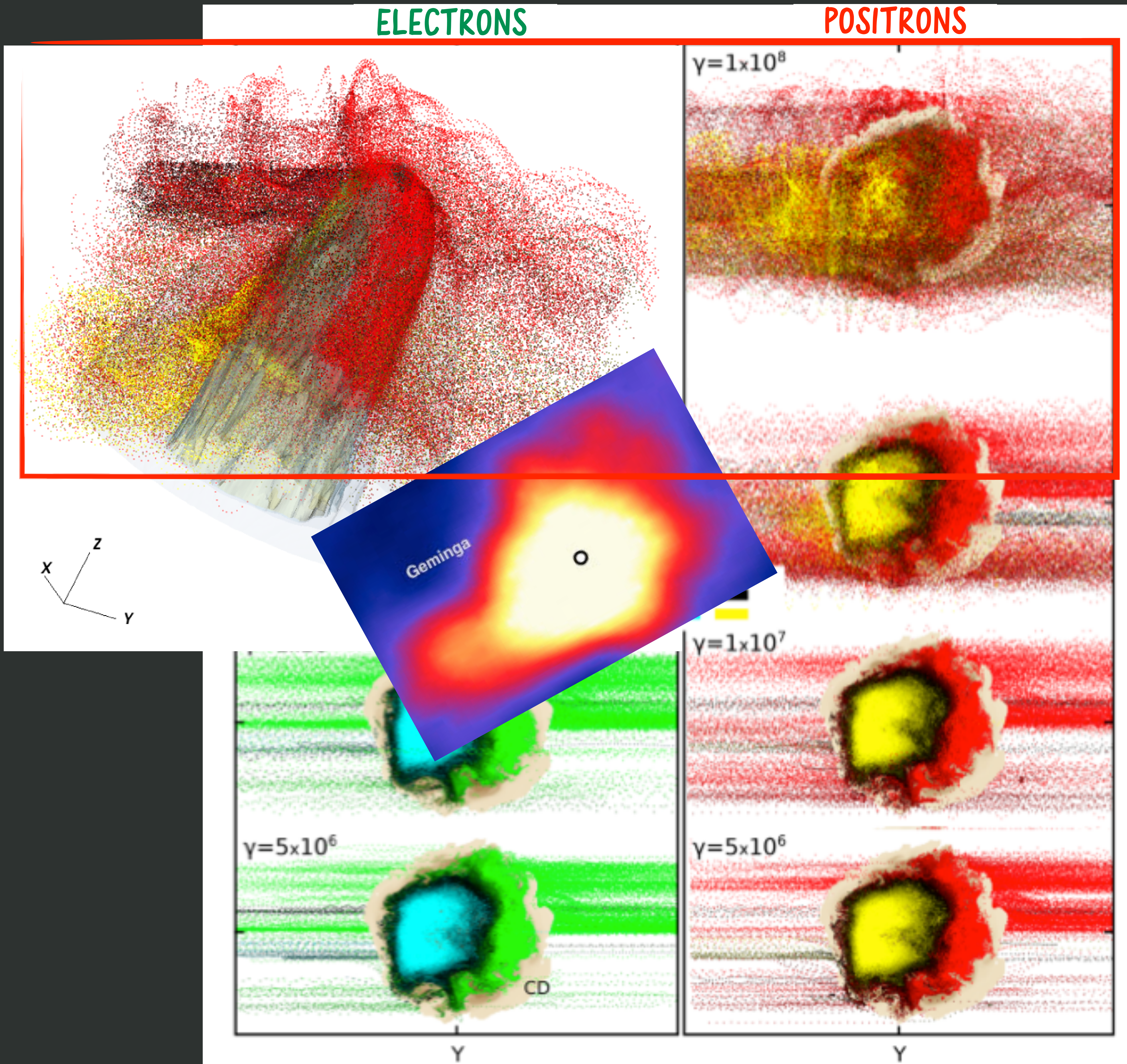
LOWER ESCAPE - ASYMMETRIC

CHARGE SEPARATION

PARTICLES DIFFUSED

PARTICLES ADVECTED

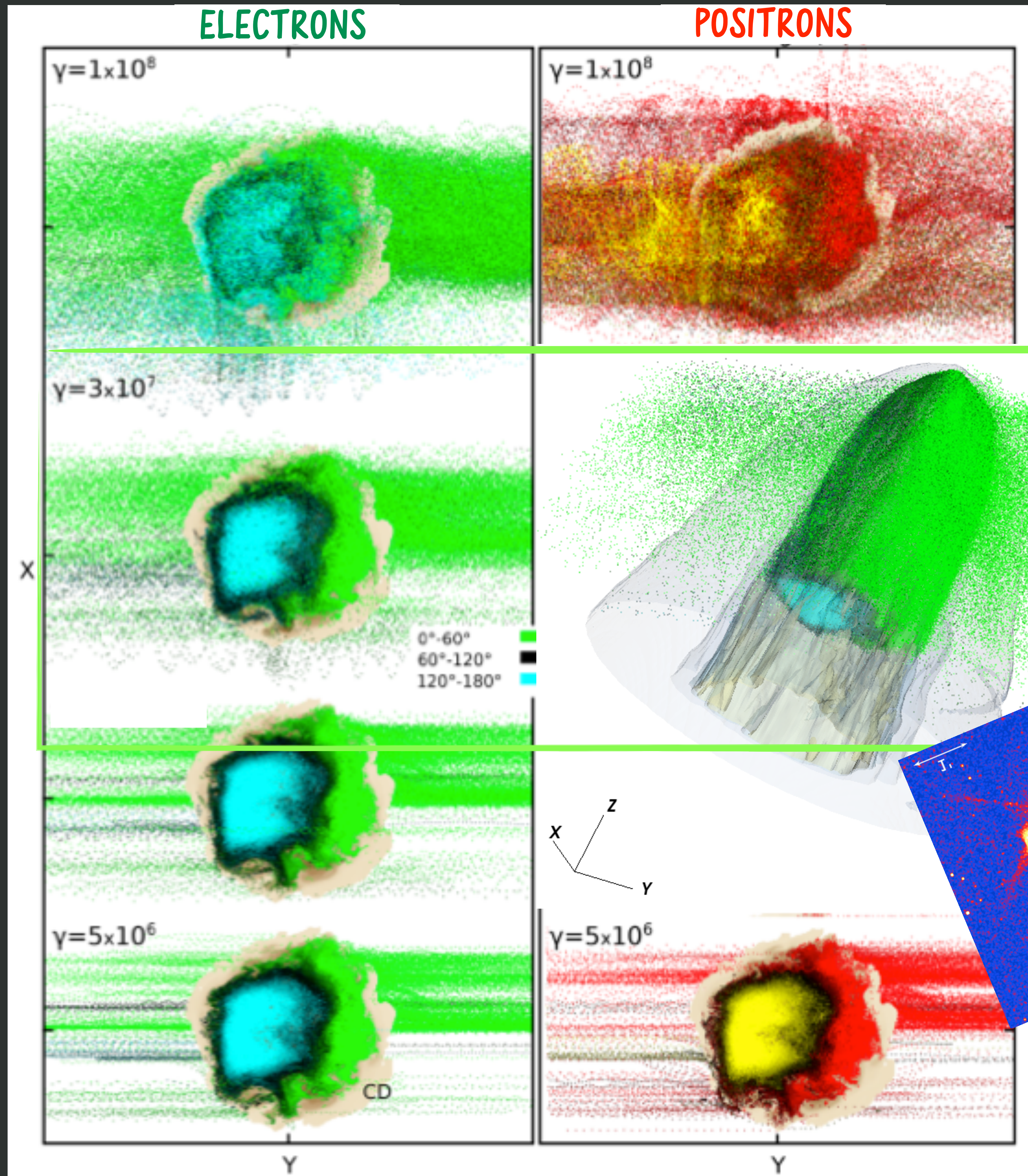
FORMATION OF DIFFERENT STRUCTURES

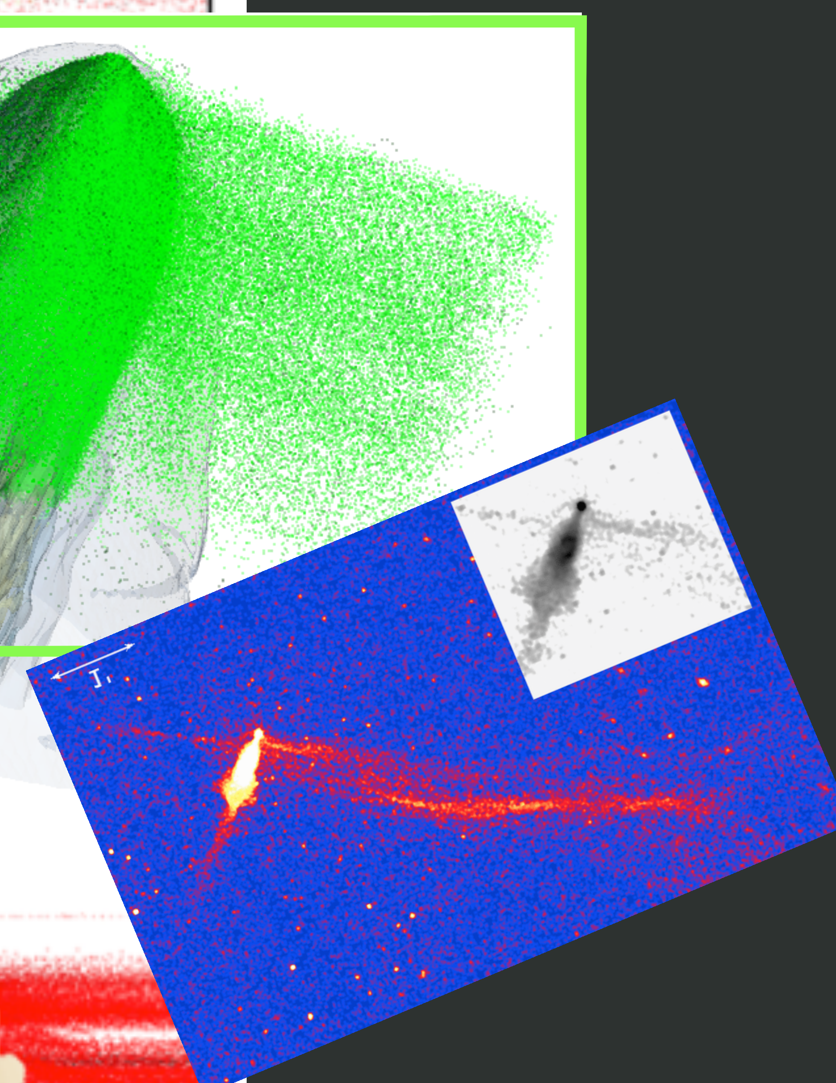


HALO LIKE

HIGH ENERGY (~50 TEV)
ESCAPE DIFFUSIVELY –
CHARGE ASYMMETRY

FORMATION OF DIFFERENT STRUCTURES





TAIL LIKE

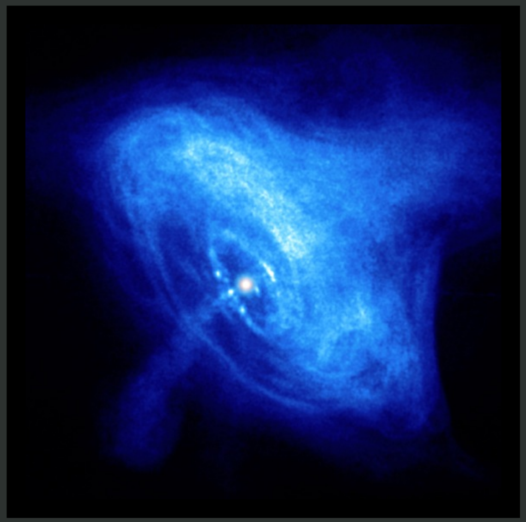
LOW ENERGY (15 TEV)

ESCAPE SPORADICALLY –

STRONG ASYMMETRY –

SMALL CHARGE SEPARATION

CONCLUSIONS



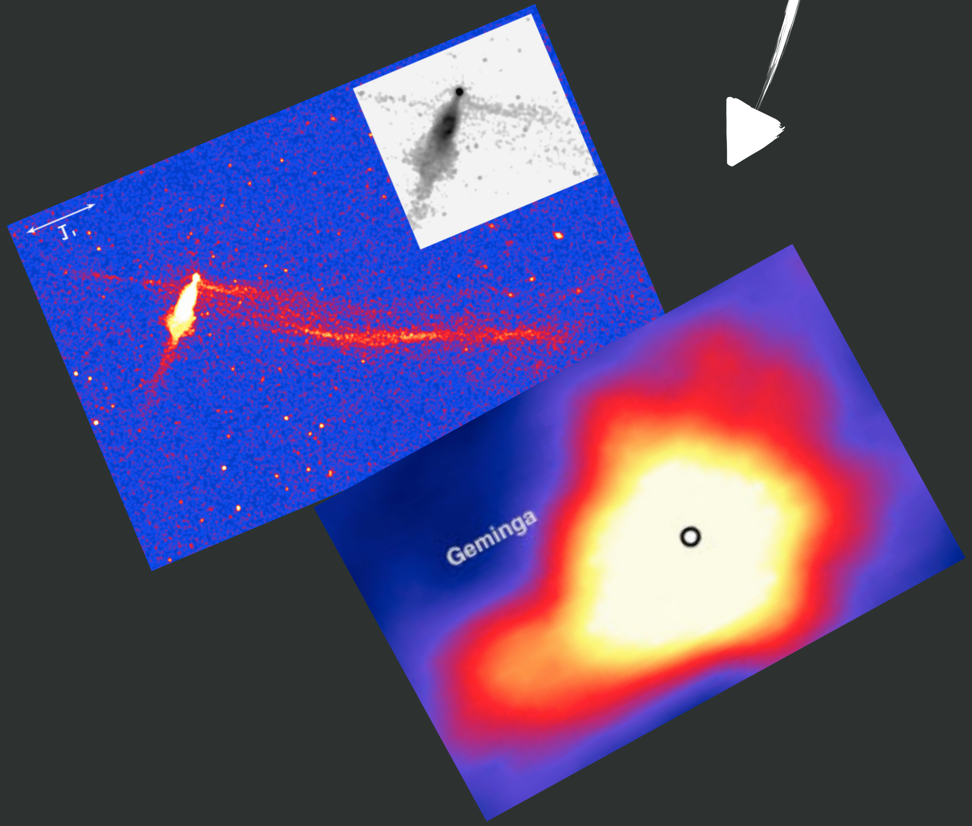
?UNIQUE MODEL?

YOUNG SYSTEMS

EXCELLENT MODELING IN MULTI-D
WITH GLOBAL PROPERTIES TO FINE DETAILS REPRODUCED

MIDDLE AGED

STILL LACK OF A GENERAL DESCRIPTION
MULTI-D SIMULATIONS AVAILABLE ONLY FOR FEW SELECTED CASES (E.G. KOLB ET AL 2017) ONE ZONE MODELS NEED TO BE UPDATED



OLD/BOW SHOCKS

3D MODELS AVAILABLE
THEORETICAL MODELING OF ESCAPING PARTICLES AND FORMATION OF TAILS VS HALOS MISSING